ZERO LEAKAGE DESIGN FOR DUCTS AND TUBE CONNECTIONS
FOR DEEP SPACE TRAVEL

CONNECTOR CONCEPT STUDIES

Volume II
of
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FOREWORD

This is volume II of a six volume final report covering work accomplished by the Research and Development Center of the General Electric Company, Schenectady, New York from 5 July 1963 to 30 June 1967. This program was sponsored by the Missile and Space Division of the General Electric Company, Philadelphia, Pennsylvania, under National Aeronautics and Space Administration Contract NAS 8-11523, "Zero Leakage Design for Ducts and Tube Connectors for Deep Space Travel."

The six volumes contained in this final report are:

Volume I	--	"Fundamental Investigations"
Volume II	--	"Connector Concept Studies"
Volume III	--	"Guide in Selecting Duct, Tubing and Gasketing Materials for Space Vehicles and Missiles"
Volume IV	--	"New Connector Designs and Testing"
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Section 1

INTRODUCTION

This is volume II of a six volume report covering work accomplished during the period 5 July 1963 to 30 June 1967 under National Aeronautics and Space Administration Contract No. 8-11523, "Zero Leakage Design for Ducts and Tube Connections for Deep-space Travel."

The work results discussed in Section 2, "Conclusions," and much of the textual material of this report apply to both permanent and semi-permanent connectors. As the term is used in this report, a "permanent connector" is one which possesses the following features:

- Requires special equipment for construction and assembly
- Requires special tools for disassembly
- Is totally destroyed upon opening

The "semi-permanent" connector also requires special tools for construction, assembly, and disassembly: it is, however, not destroyed until it has been disconnected several times. The "separable" connector is one which can be made up and disconnected with only common hand tools such as standard wrenches, screwdrivers, etc.

Permanent connectors are by definition inapplicable to final closure of systems. Final enclosures and all connections that may need to be opened for test, inspection, or replacement of defective components, presently utilize separable connectors. Separable connectors, however, often leak. The basic purpose of this program is through the exploration of various joining techniques and concepts, to develop semi-permanent connectors with which to replace separable connectors in all but the most frequently opened joints. The scope of the work to date is summarized below.

SCOPE OF WORK

The work accomplished in this period involved a welding technique which is at present used in only permanent connectors, to determine whether limitations of the process in connector design are inherent or avoidable. Joining concepts presently used in applications other than connectors and other novel joining concepts were also considered. For instance, it was assumed that exotic and composite materials might best satisfy the total requirements for fluid systems. These, however, resulted in new connector problems and thus connectors for lined tubes came to be considered.

The following specific joining methods were analyzed:

- Ultrasonic welding

- Explosive forming
- Magnetic forming
- Adhesive bonding techniques
- Fusion welding studies
- Lined tubing and ducts

The experimental data obtained was analyzed to determine the suitability of each method to the present program.

Section 2

CONCLUSIONS

Specific conclusions derived from these connector concept studies are divided by subject and listed below. It might be noted that cold pressure welding and diffusion bonding have been investigated and these procedures are written up in Vol. IV of this final report.

ULTRASONIC WELDING

Ultrasonic equipment is not currently available for making the seal for zero leakage fluid connectors within the range of the National Aeronautics and Space Administration requirements.

EXPLOSIVE FORMING

Several tube joints were made using aluminum tubing and a solid metallic mandrel to keep the tube from collapsing. These joints were pressure tight when tested up to the yield point of the tube material and metallographic photographs showed welding had occurred in the joint area.

Two problems arose in making joints using the explosive technique. The first resulted from the means used to detonate the main sheet of explosive wrapped around the tube. A high charge detonation cap joined to a lead-in length of explosive located outside the joint fixturing was detonated and as the explosion advanced along the lead-in into the joint fixture, explosive amplification results from a more concentrated charge where the lead-in joined the main sheet charge. Because of this, tube deformation in this area was excessive, and in some test resulted in the rupture of the wall.

A second problem area appeared in the form of explosive reinforcement produced by the interaction of two travelling explosive waves. Since the sheet of explosive wrapped about the tube joint's periphery was detonated at one point, two separate explosive waves were created and travelled circumferentially away from the point of detonation. At a point on the joint's periphery, located 180° from the point of detonation, wave amplification resulted, causing, in some cases, a rupturing of the tube wall.

Neither of these problems however, present themselves as major ones. From the results of this preliminary feasibility study, it can be said that this technique contains much promise for application to the fabrication of connectors. Should light-weight fixturing be developed, it would lend itself well to practical in-place permanent connectors.

MAGNETIC FORMING

The magnetic forming process, in general, was successful in fabricating a number of good leak-tight joints with sound mechanical strength. However, because of a problem inherent in the split shapers allowing a non-uniform force field, the results of the tests were not of high enough degree of success to warrant the adoption of this process as a means of making a permanent connector. A segment of the test program dealing with the making of good joints repeatably showed that the percentage of acceptable joints made was unsatisfactory. Nevertheless, the process is one which allowed for easy workability, cleanliness, and ease of handling. Also, no expensive fixturing other than a machined coil shaper piece was required.

ADHESIVE BONDING TECHNIQUES

Epoxy bonding has long been used in the aircraft industry and elsewhere. However, special potential problems have arisen when this form of bonding has been employed as the joining and sealing mechanism in a connector. Tests were made to isolate and solve these problems. The results, where only one formulation of adhesive was used, looked very promising. Since only a 10° tapered joint was used in these tests, it is anticipated that the strength of these joints can be almost doubled by employing 5° tapers. Besides strength, it was also proved that adhesives can be very easily used to form zero leakage connections. Therefore, in integrated connectors, they could be employed as the sealing part of such connectors and in fact used to replace the gasket.

Since the results of the thermocycling tests looked very promising, the difference in the expansion of the various materials tested does not appear to be a critical factor. However, a non-brittle material was especially chosen for these tests and to the extent that this is or is not feasible, the results may be optimistic.

FUSION WELDING STUDIES

From the point of cleanliness, fusion welding is well suited to the making of permanent duct joints.

LINED TUBING AND DUCTS

Metal components, notably aluminum and stainless steel, have been used for most fluid systems to date. During this contract period, lined tubes which could handle fluids not compatible with metals were considered for future use. It appears that joints in such systems can be satisfactorily made. However, because of the relative lack of definition of the problem and the range of variability that could be visualized, no attempt was made to design, build, and demonstrate such a connector.

It has been demonstrated that teflon lined pipe can be used over a temperature range of -100°F. to + 500 $^\circ$F. and possibly down to -420°F. Pressures as high as 900 psi have been contained for short periods of time. Proper flange designs could result in containment of high pressure for unlimited time periods if leakage by permeation is not a problem.

Teflon lined pipe, as opposed to other conventional materials, has the following advantages:

1. It is compatible with all propellants except fluorides.
2. It is a thermoplastic that may be heat-sealed.
3. It is a tough material, having the ability of withstanding flexing, impact, and elongation.
4. It is thermally and electrically resistant, and thus provides a thermal insulation for cryogenic fluids and electric isolation to sparks or static electricity.

Teflon, like other plastics and rubbers, has the disadvantage of being porous. Leakage by permeation of gas through the plastic is approximately 10^{15} times greater than through metals. Therefore, since it is presumed that the fluid is reactive with the pipe and that the liner must protect the pipe and form a seal at any joint, it is important to consider whether these presumptions are likely to present serious problems.

Section 3

RECOMMENDATIONS

Based on the test results obtained during this program, the following recommendations are made.

ULTRASONIC WELDING

The utilization of ultrasonic equipment to obtain zero leak connections under field applications is not at the present time a possibility. If one or several of the advantages of the ultrasonic process over other techniques is required, it is recommended that an investigation be made to determine whether the required development of the ultrasonic equipment is justified.

EXPLOSIVE FORMING

In regard to explosive forming, it is felt that the concentration of explosive in the sheet was too high and that a lower concentration sheet would have to be sought in order to make the process acceptable. Additionally, more effort will have to be placed on finding a suitable support for the tube's inner wall and for protection of the tube's surface during detonation. Preliminary tests indicated the practicality of being able to accomplish both these aspects. However, each is far from finalized and requires more development.

MAGNETIC FORMING

It is recommended that some effort in the magnetic forming process be made to overcome the problem of the "split" coil shaper. Perhaps the idea of a one shot throw-away coil would be applicable. If this could be successfully produced it would be adaptable to field use and thereby eliminate the obstacle of making the process field operable.

ADHESIVE BONDING TECHNIQUES

Adhesive bonded joints have proven to be high in strength and possess an adequate degree of leak-tightness. Therefore, they can be used with confidence in many present day applications. Furthermore, when compatibility between the adhesive and the operation fluids is established added consideration should be given to their use. In addition, the use of cemented joints (i. e. epoxy and similar materials) should be seriously considered where permanent joints are needed and welding cannot be used. Further tests to prove suitability are recommended.

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FUSION WELDING STUDIES

The tests conducted on sound fusion welds have shown that these can be made without contaminating the duct system. As a result, the fusion weld process, when viewed from this aspect, should not be ruled out as a joining means, and it is recommended that this approach remain a possibility in duct joining applications. Also, further consideration should be given to the development of techniques for making and inspecting final closures by fusion welding. Chances for success are judged to be high and could lead to weight reduction and improved reliability, particularly in larger systems.

LINED TUBING AND DUCTS

It is recommended that specific application parameters be reviewed in light of the advantages of a lined duct system. It is felt that this system should be given further consideration whenever the application permits.

Section 4

ULTRASONIC WELDING

DESCRIPTION OF THE PROCESS

The ultrasonic welding process was investigated in order to determine its feasibility in the making of leak-tight seals for fluid connectors. This is a method widely employed for the joining of similar and dissimilar metals by the introduction of high frequency vibratory energy into overlapping metals in the area to be joined. It has been found that a good bond can be produced without arc or spark, without melting the pieces to be joined, without the formation of a cast structure, and with negligible loss of thickness.

In this process the weld occurs when a tip, clamped against a workpiece, is made to oscillate in a plane parallel to the weld interface. This produces dynamic stresses in the metal resulting in elastoplastic deformations which produce a moderate temperature rise in the weld zone. In no instance involving monometallic welds made under normal conditions, has there been any evidence of melting of the metal in the weld zone (See Ref. 1)

ADVANTAGES AND DISADVANTAGES OF ULTRASONIC WELDING

Advantages

A listing of the various advantages of ultrasonic welding are as follows:

1. Dissimilar metals can be joined (Stainless 321 to Aluminum 6061-T6 have been welded together), (See Ref. 2).
2. Normally, surface preparation is not highly critical since vibratory displacements disrupt normal oxides. Heavy scale should be removed by mechanical abrasion or chemical etching. If this is accomplished, the elapsed time before welding is not important. (See Ref. 3).
3. Thin foils of 0.00017 inches can be welded (See Ref. 3).
4. No inert atmosphere is required.
5. Hermetic seals have been obtained by ultrasonic welding and tested. The General Electric Company has adopted the ultrasonic welding technique in the production of silicon rectifiers (See Ref. 3).
6. Since no melting takes place, the parent material is relatively undisturbed. In some investigations a weld strength equal to 80 percent of the parent material was achieved (See Ref. 3) .
7. No contamination of the weld area occurs (See Ref. 3) .

8. Temperature increases of only a few degrees Fahrenheit result from welding.

9. There is no indication that welds are susceptible to corrosion.

10. The power source and welding head can be located 100 feet or more apart.

11. With proper setup and maintenance of the welding unit, the dependability of the welding process is very high.

12. Although thick materials cannot be welded, the limiting factor is the thinner of the pieces to be joined; i. e., a thin sheet within the limiting size can be joined to metal of any thickness.

Disadvantages

The major difficulties associated with ultrasonic welding are as follows:

1. The maximum thicknesses that can be welded are 0. 1 inch for aluminum and 0. 02 to 0. 05 inch for harder materials.

2. Depending on the material to be welded, equipment can become very large.

3. Low power efficiency is obtained.

FIELD APPLICATION

The welding equipment ultimately decided upon for use must be capable of performing the weld under field conditions. The major fallacy with ultrasonic welding equipment is that it could become very large. This problem was further investigated and it was found that commercially available ultrasonic welders range from 20 to 4000 watt units. The larger the power requirements the larger the physical size of the unit. At the present time ultrasonic spot welders are available with a welding head weighing only 12 pounds and having the capability of welding aluminum wire from 0. 0005 to 0. 020 inch in diameter.

Ring welders which make welds on diameters from 1/8 inch to 2 1/2 inches are available from the Sonobond Corporation in Pennsylvania. These commercially available ring welders cannot be adapted to permanent type connectors since they are not portable. However, it appears possible to develop a portable, continuous seam welder where the power requirements would be much smaller when a progressive weld is made instead of welding an entire ring at once. The tube could be designed so that the ultrasonic weld forces needed for bonding would be small. Sealing materials of approximately 0. 005 inch thick can be used. A practical ultrasonic welder for connectors would then have some of the characteristics of a light, portable spot welder and some of a continuous seam welding machine.

One manufacturer of ultrasonic equipment was consulted, and it was estimated that a 300 watt seam welder would adequately form the hermetic seal for fluid connectors. The basic characteristics of this 300 watt seam welder are:

1. The ultrasonic head is 3 inches in diameter and 14 inches long.
2. The maximum thickness of 1100 series aluminum that could be welded is 0.010 to 0.012 inch thick.
3. A clamping force of 80 to 100 pounds is required across work pieces and the ultrasonic head.

As a clearance about the periphery of the tube flange of only three inches is obtainable, the use of ultrasonic welding is restricted in making field welds. Present techniques require the 14 inch dimension to be perpendicular to the duct center line thereby requiring a dimension much greater than the three inches allowed.

Section 5

EXPLOSIVE FORMING

INTRODUCTION

The technique of explosive forming or joining was analyzed as part of this program of investigation and evaluation of the processes by which permanent tube connections may be made. It was hoped that a method for joining permanent tube connectors could be developed which would offer little disadvantage and could be successfully adapted to a number of different situations.

It was initially realized that some problems such as the danger of the explosives would have to be overcome. However, with proper fixturing it was felt that this aspect could be minimized.

Overall, explosive forming has a marked economic advantage. Explosives are relatively cheap and even though necessary fixturing would be somewhat expensive when all costs and time involved are considered, the method should prove to be quite inexpensive. It was visualized that the greatest portion of time would be consumed in assembling the joint and fixturing. Once this is done, the charge can be ignited and the joint formed instantaneously.

Concurrent with this investigation of explosive forming, an analysis of magnetic forming was conducted, the latter being reported in Section 6 of this volume of the final report. So that adequate comparison between the two methods could be made, two sizes of tube (3/8 inch and 2 inch) were selected as representative of the range over which these processes would be applicable.

TECHNICAL DISCUSSION

When explosives are mentioned as a means of effecting a joint, the containment of the explosive charge immediately comes to mind. While this poses some drawbacks in the way of handling and fixturing the massive containment, it was felt that these disadvantages could be overcome.

A number of joints were made by assembling two tubes, an insert, and an explosive wire wrapped around the tubes, over the area to be formed. The appearance of a 2 inch tube assembly before firing and of the joint after firing are shown in Figures 1 and 2, respectively. The details of the tubes and inserts used for this first series of tests are the same as those shown in Figures 19 and 20.

A DuPont modified detonation fuse (MDF) with A-5 explosive core wire was used. The detonation produced an excellent depth of draw with adequate energy distribution except at the ends of the wrap. Here, the energy

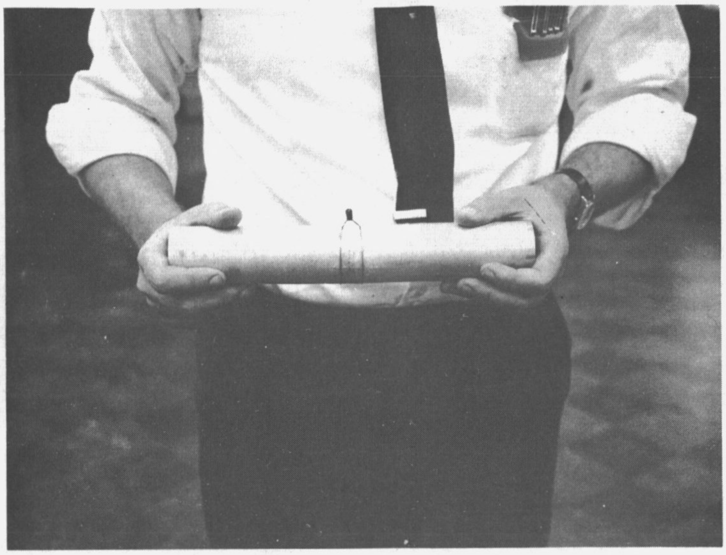


Figure 1. Two-inch Sample Joint-prepared with Two Wraps of 073 inch MDF A-5, Ready for Firing.

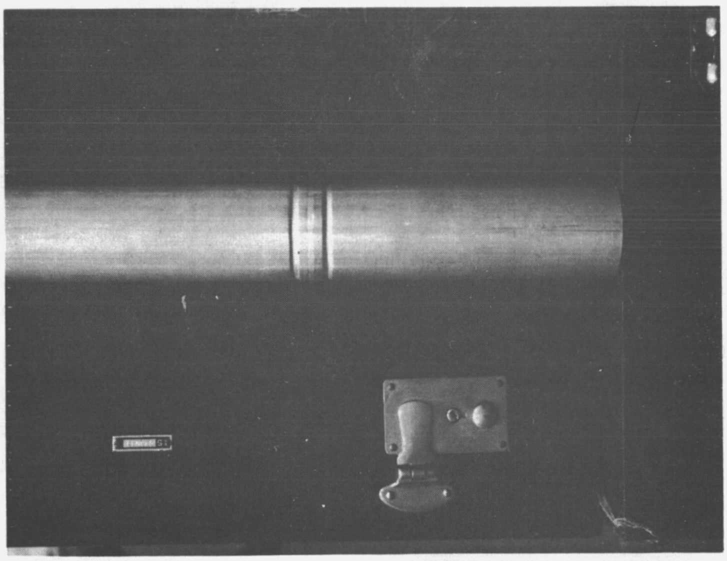


Figure 2. Joint After Firing Showing Excellent Draw Depth and Uniformity (End Effect not Visible in Photo).

distribution was non-uniform due to the end effect. This, however, can be controlled by surrounding the ends with containment. The sample used was sectioned to determine whether cold welding was achieved. This is of prime importance to assure that a structurally sound joint with no leakage is formed. In these tests no evidence of leakage was found and the end results of the sectioning are shown in Figure 3.

In order to cross-section the connector, the assembly was first potted in an epoxy and then cut and etched. Several important phenomena could be noticed. These are illustrated in Figure 3. First, on the right side of the connector, the explosive charge was placed in an eccentric manner with respect to the insert depression and knife edge. The resultant tube deformation is not that which was intended and hence a good mating with the knife edge was not formed. Conversely, the explosive charge forming the left hand junction has been satisfactorily placed and the resultant metal deformation appears symmetric. It can also be noted in Figure 3 that the eccentricity of the explosive charge with respect to the center of the insert depression on the right hand end has caused the tubing to be pushed longitudinally into the insert centering rise. High magnification inspection of the end of the tubing and the insert centering rise showed extremely close contact between the two metals. While this was unintentional in this particular experiment, a possible seal there was investigated. Since the non-uniformity of the tube collapse in the knife edge region indicated absence of a seal, a leak check with a vacuum inside the fitting was run and also showed the absence of a seal at the tube ends.

Figure 4 shows a high magnification photo of the knife edge of the insert and the opposing portion of the tubing. The aluminum components pictured are 6061-T6 tubing and 2024-T3 insert. It can be noticed in this figure that, while the explosive charge caused definite plastic deformation in the tubing, the elastic springback was sufficient to cause separation between the tubing and the knife edge. Hence, if the seal intended was to occur in this location, the junction would not be satisfactory.

Upon completion of this initial test phase, an effort was undertaken to more effectively apply the high forces generated by containing them through proper containment fixtures. Other connector joints were designed to better utilize the forces generated. More directly, it was felt that the new fixturing and tube joints would provide basic information regarding the cold welding process and whether it could be applied to the task at hand.

Two different kinds of connections were tried, namely a flange type connector, Figure 5, and a straight sleeve joint, Figure 6.

The flange type connector was tried in two different ways:

1. An explosive sheet was detonated on top of a 6° flared flange. The 6° angle is critical, according to the available literature on this

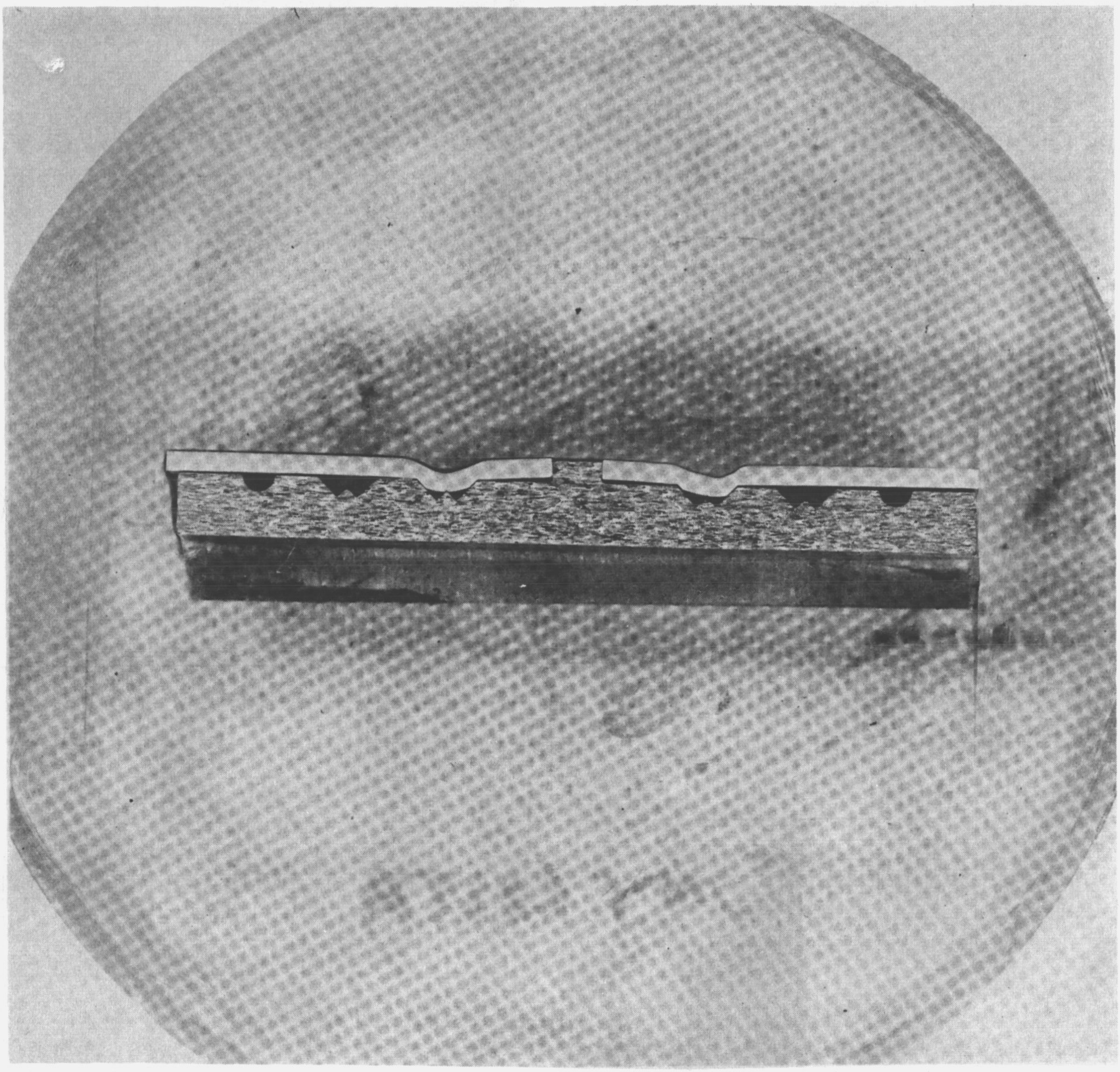


Figure 3. Cross-section of Joint Constructed with Explosive Wire.

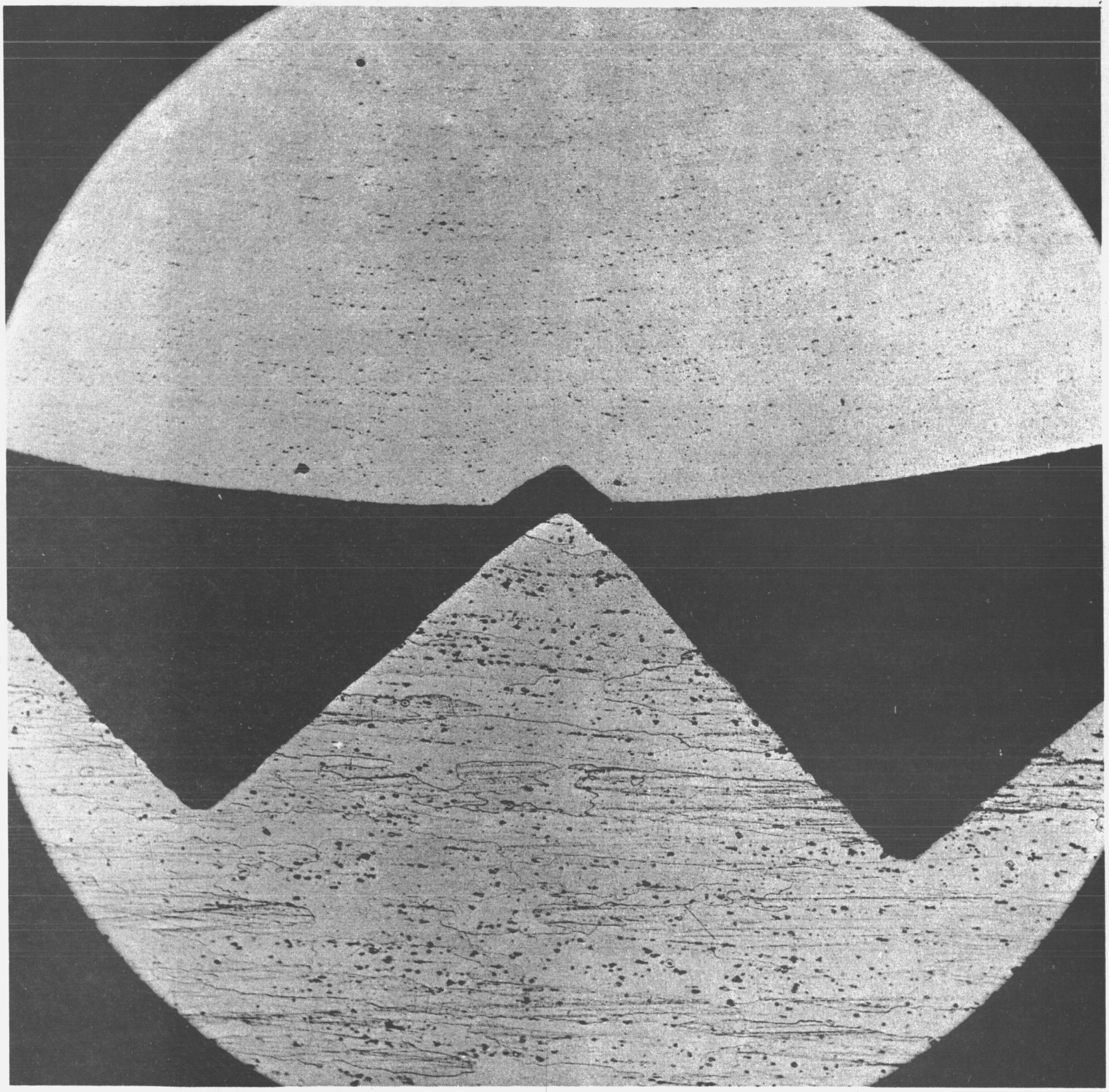


Figure 4. 100X Magnification Cross Section View of an Explosive Formed Permanent Connector. (Shown is 2024-T3 Aluminum Insert (Bottom) and 6061 Tubing (Top), this is the Same System as Shown in Figure 3).

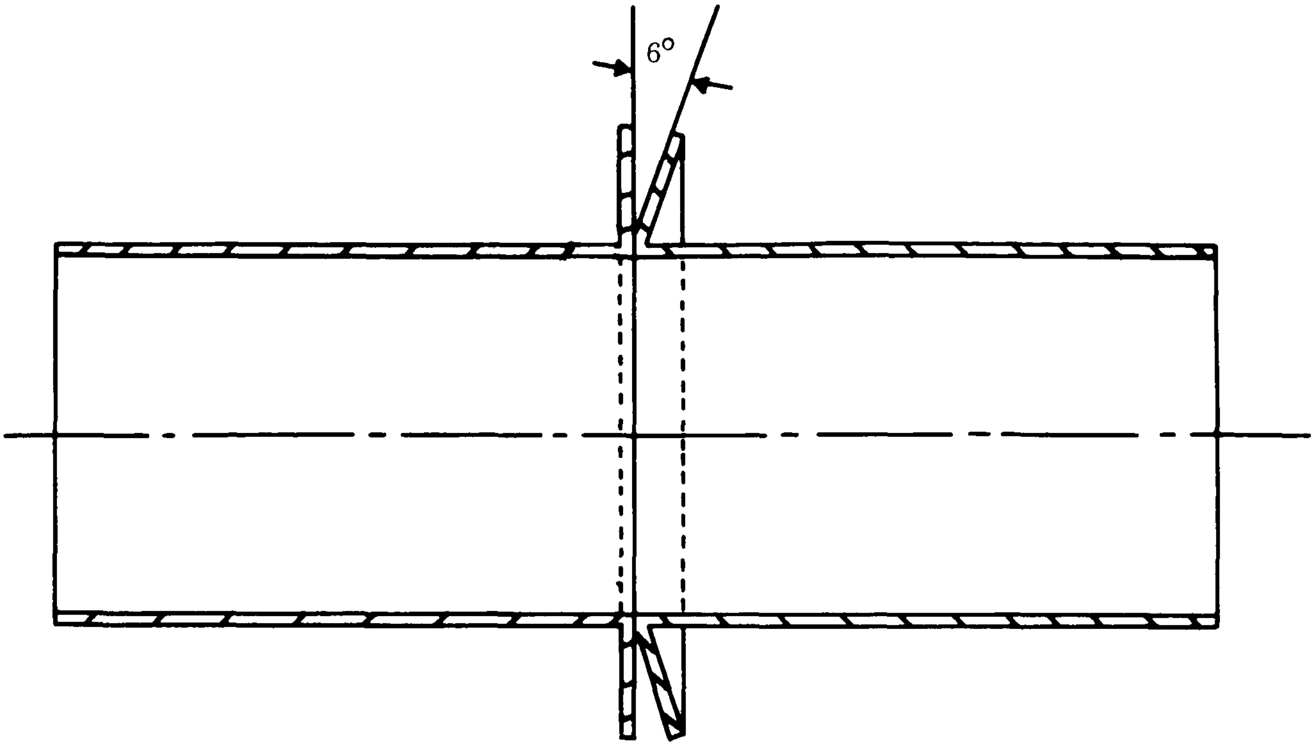


Figure 5. Explosive Forming Flange Connection.

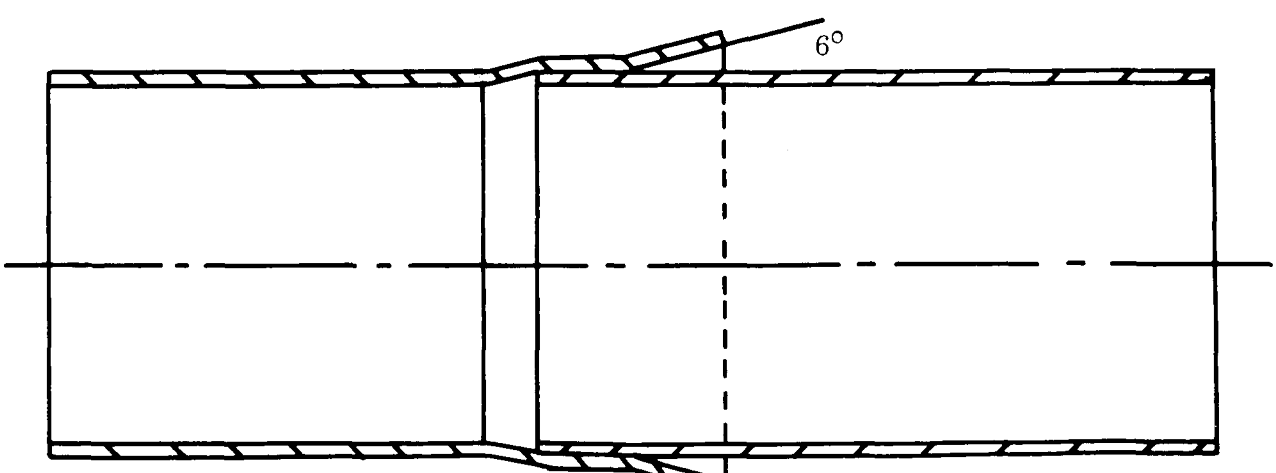


Figure 6. Explosive Forming Sleeve Type Connection.

process (Ref. 4) because it is necessary in order to obtain relative velocities between the two materials to be joined. In this case good welds were not achieved. However, these first tests employed a charge of PETN (Pentaerythritetetranitrate) explosive which was too large. A problem of protecting the tube from damage by the explosive also arose. Figures 7 and 8 show the setup used for these tests, as well as the fixturing required to contain the charges employed.

2. In the second trial the tube samples were folded together and held in two buffer plates connected by a hinge. This setup is shown in Figure 9. An explosive charge was detonated on top of one of these plates and it was observed that no welding took place at any of the pre-set angles used.

A straight sleeve joint was tried and appears more promising than the flange type joint. Instead of the PETN explosive sheet (3g per in^2, which was too high a charge) a plastic bulk explosive material in the form of a collar was placed around the flared tube and detonated. Although this material was hanging loose and did not stick to the tube, welding took place as shown in the photomicrograph, Figure 10. Figure 11 shows the setup of this test with the inside mandrel and the outside cover. A solid steel mandrel was used for the tube tests to prevent the tube from collapsing. In actual application, the mandrel would be replaced by a hollow insert capable of withstanding explosive forces. Later tests showed that a 1/4 inch wall thickness insert made of 2024-T4 aluminum was sufficient.

Since the bulk material is hard to properly distribute and keep in place, attempts were made to find a substitute. It was decided that liner charges and primer cord are locally strong. The lowest energy explosive sheet available on the market was DuPont EL-506C with 1 g/in^2 charge density. Tests with the material were conducted on the straight sleeve joint. In these tests, good welds were achieved in most cases. Tube protection appeared to be no longer a serious problem since tape wrapped around the tube prior to applying the explosive adequately protects the tube surface.

A basic problem encountered was the presence of irregularities of the weld both at the beginning and end of the shock wave. A continuous ring of explosive sheet around the tube has to be ignited, resulting in a somewhat higher charge at the ignition point. From this, an irregularity of the weld is evident as shown in Figure 12.

After ignition, two shock waves travel around the tube and meet 180° opposite the ignition point. There the waves cause an indentation which forms the second irregularity of the weld (See Figure 13). In some cases this indentation allowed a leak.

The generation of a weld is dependent on the velocity of contacting, which in turn, depends on the geometry, mass, and accelerating force.

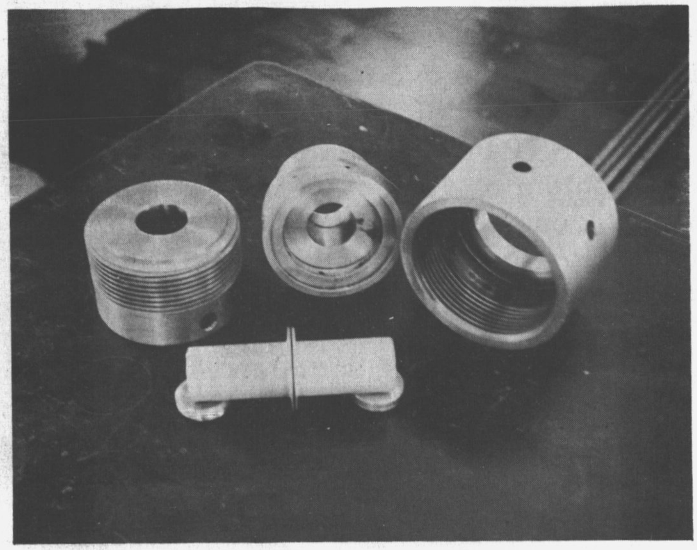


Figure 7. Flange-type Connection Before Forming Together with Disassembled Cover.

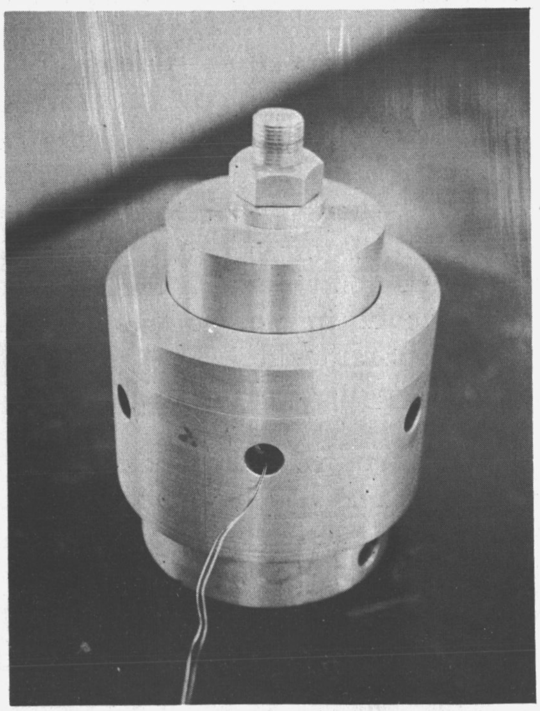


Figure 8. Flange-type Connection Ready to Shoot With Protective Cover in Place.

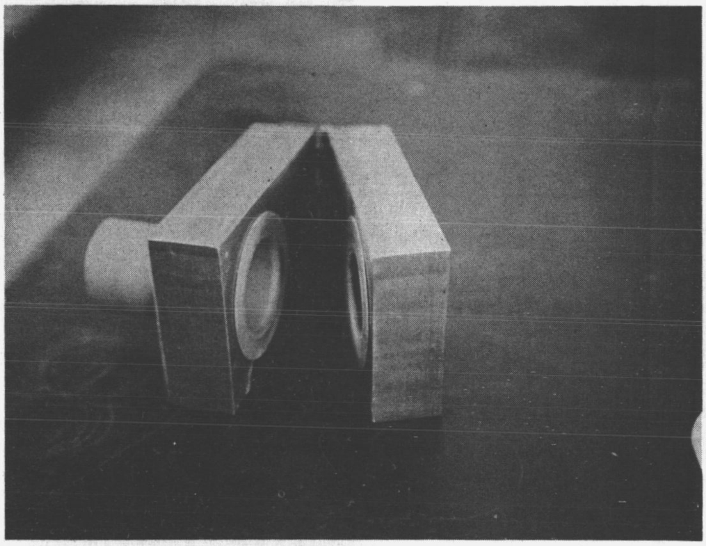


Figure 9. Flange-type Connection Mounted Between Buffer Plates. Explosive Sheet is Detonated on Top of One of the Plates.

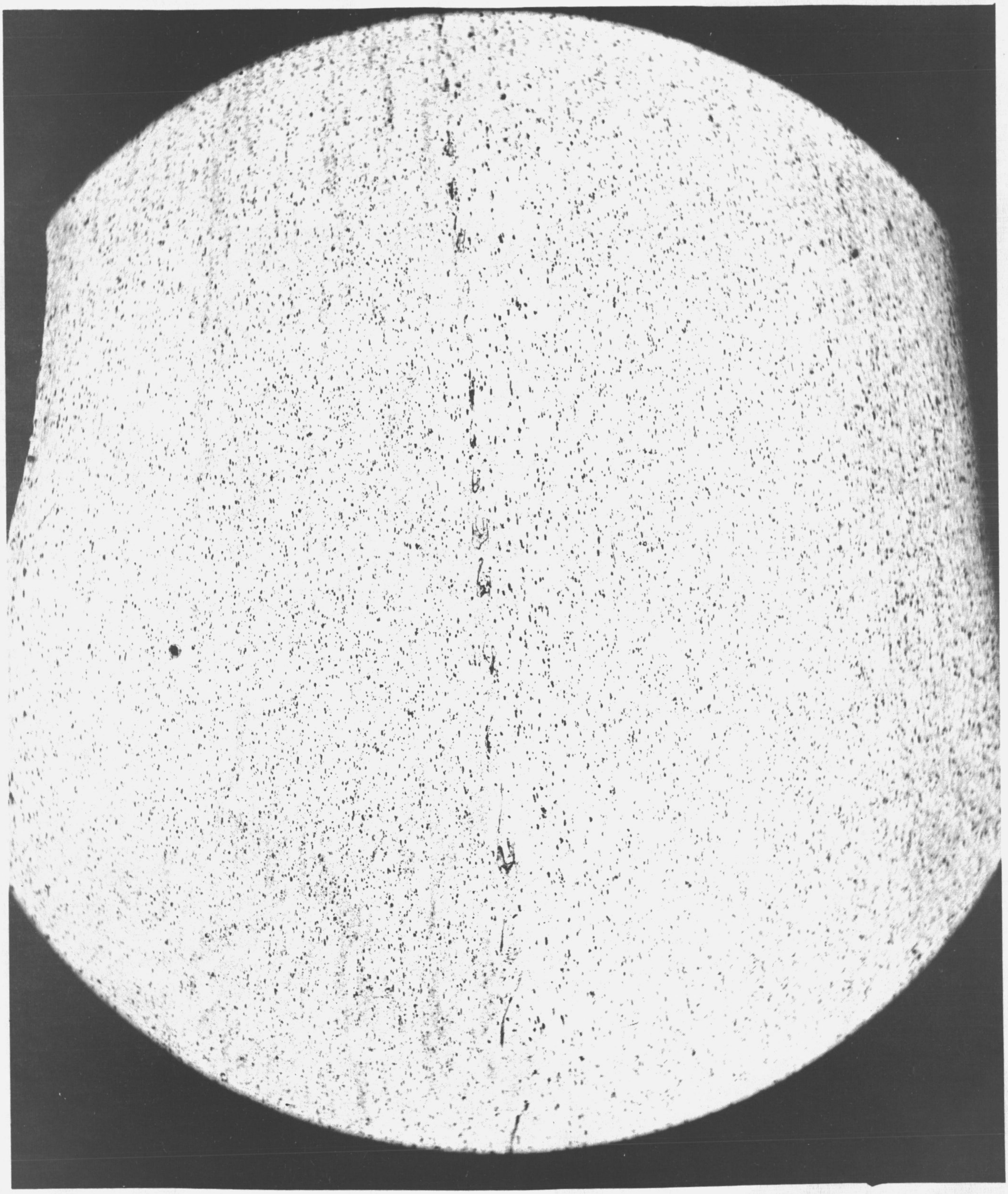


Figure 10. Sample of Explosive Welding Performed with a Straight Sleeve Joint by Detonating a Layer of Bulk Material.

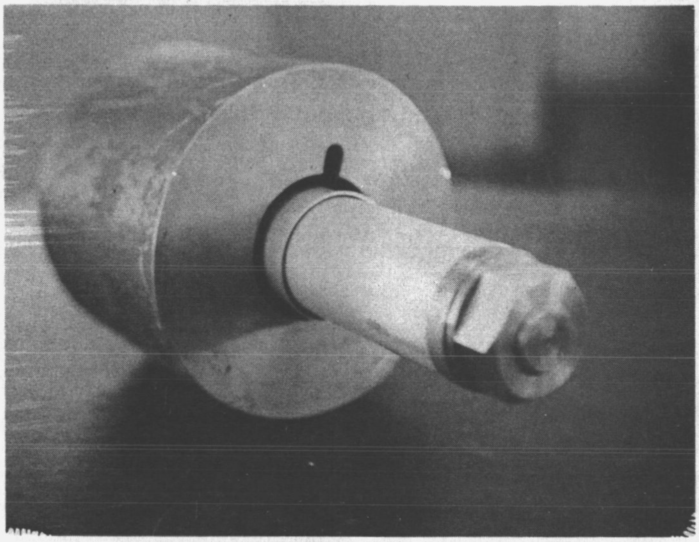


Figure 11. Straight Sleeve Joint Mounted in Protective Cover (Note that the Mandrel Keeps the Tubes in Place and Prevents Collapsing).

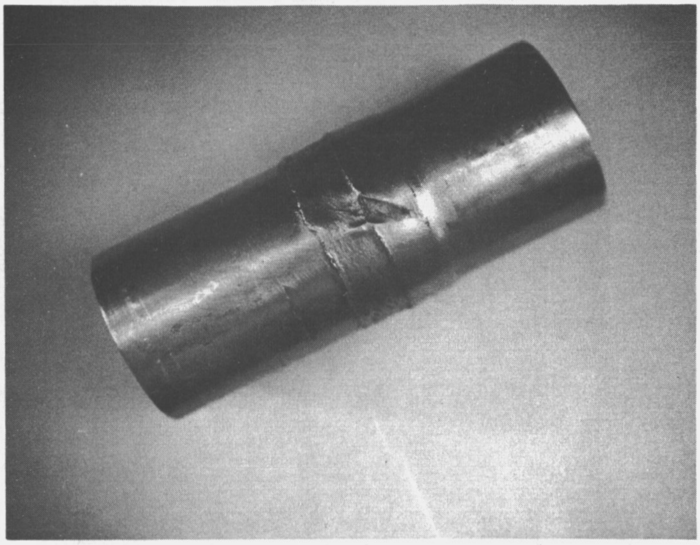


Figure 12. Ignition Point of the Continuous Explosive Sheet Ring.

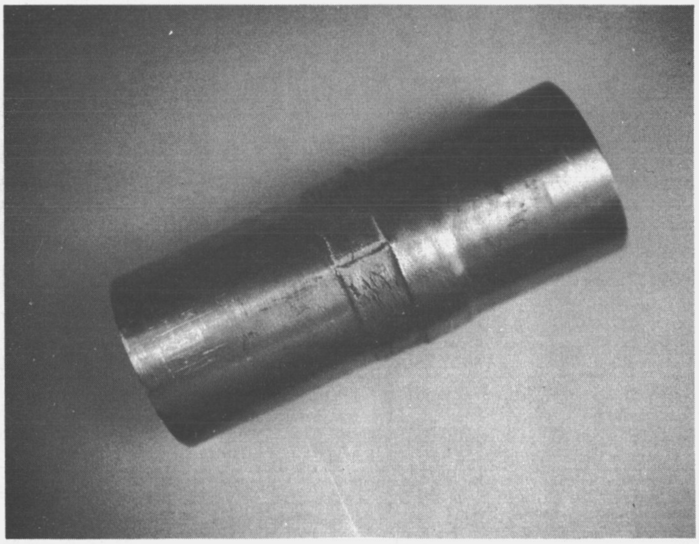


Figure 13. Indentation where the Two Shock Waves Meet.

Three different photographs taken from a weld of a tube joint show the effects. The locations are indicated in Figure 14. Figure 15 was taken at the tip of the angle (Position III Figure 14), Figure 16 at the middle of the weld (Position II of Figure 14); and Figure 17 shows the end where the acceleration was highest (Position I, Figure 14). Where the welding starts, at the tip of the angle, the materials make very good contact, but some increase in impact velocity is needed until the surface jetting process begins and welding is promoted. The beginning of the waviness in the weld line can be seen at the bottom of Figure 15. In the middle of the weld this surface jetting is very eleborate as seen in Figure 16. At the end of the weld where the impact velocity is very high the waviness tends to vanish. Here a kind of diffusion occurs as seen in Figure 17. The darker shades on one side of the weld indicate the metal working that has taken place. The shades increase from the start of the weld at the tip of the angle, Figure 15, to the end in Figure 17, where the most deformation and bending occurs.

Position IV in Figure 14 indicates the point where the two shock waves met. An indentation can be seen but the material did not break. Figure 18 illustrates a photomicrograph of this location. The indentation in the shadowy work hardened material can be seen. No actual welding took place in this plane, again due to the fact that the location is too close to the tip of the angle where the impact velocity was still small. In other planes the welding occurred as shown in Figure 15, 16, and 17.

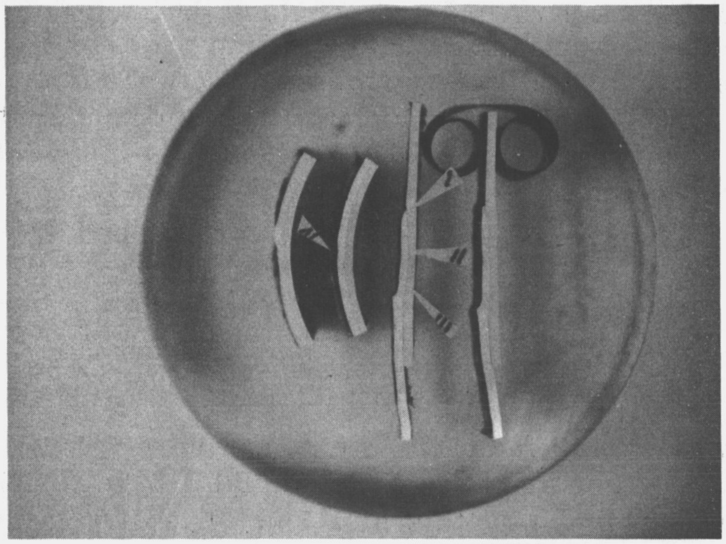


Figure 14. Location of Points where Microphotographs were Taken. (The Section to the Right Position IV Shows the Ignition Point in the Same Horizontal Plane).

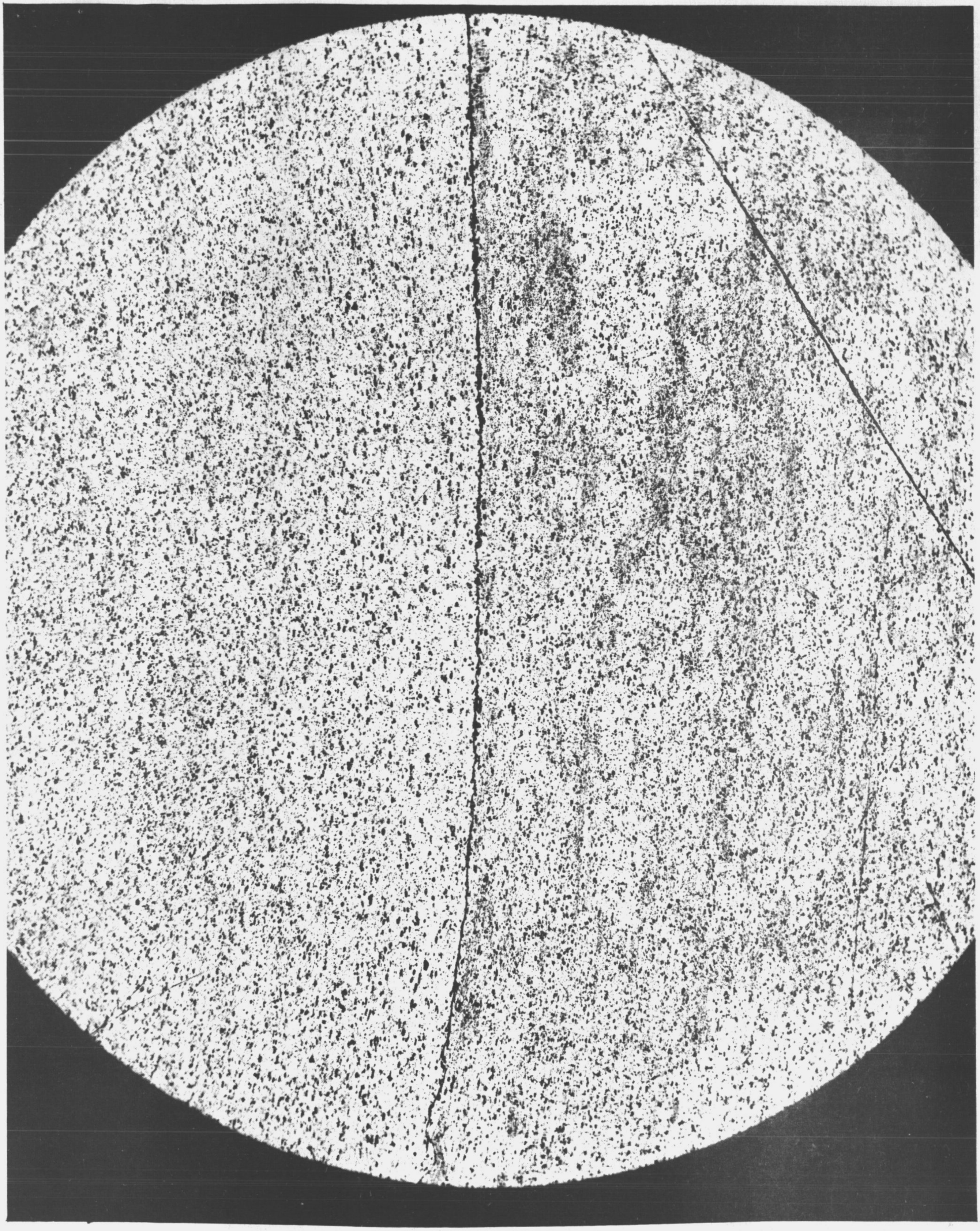


Figure 15. Start of Weld at Low Impact Velocity.

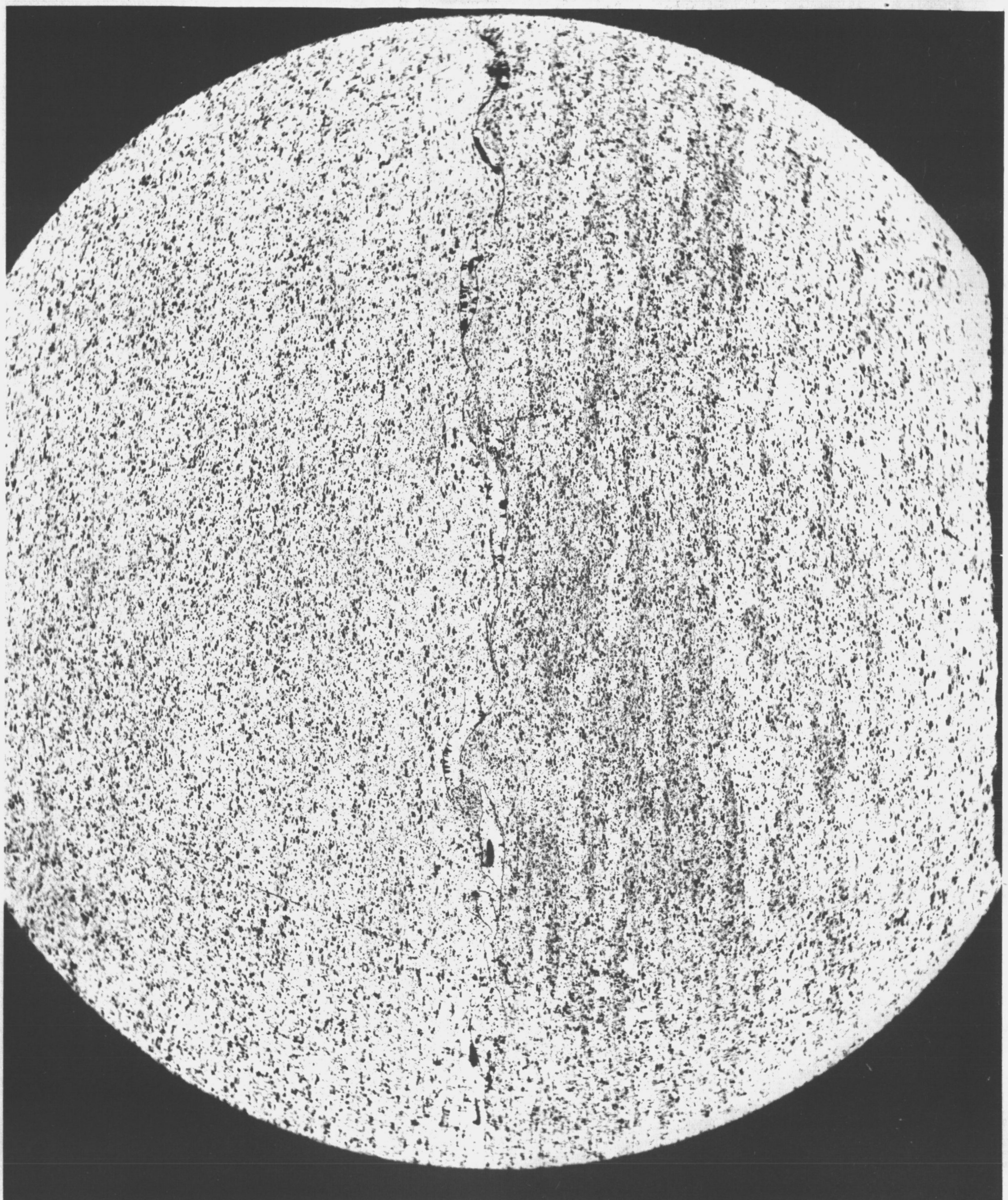


Figure 16. Middle of Weld Showing Waviness of Weld Line.

Figure 17. End of Weld at Highest Impact Velocity.

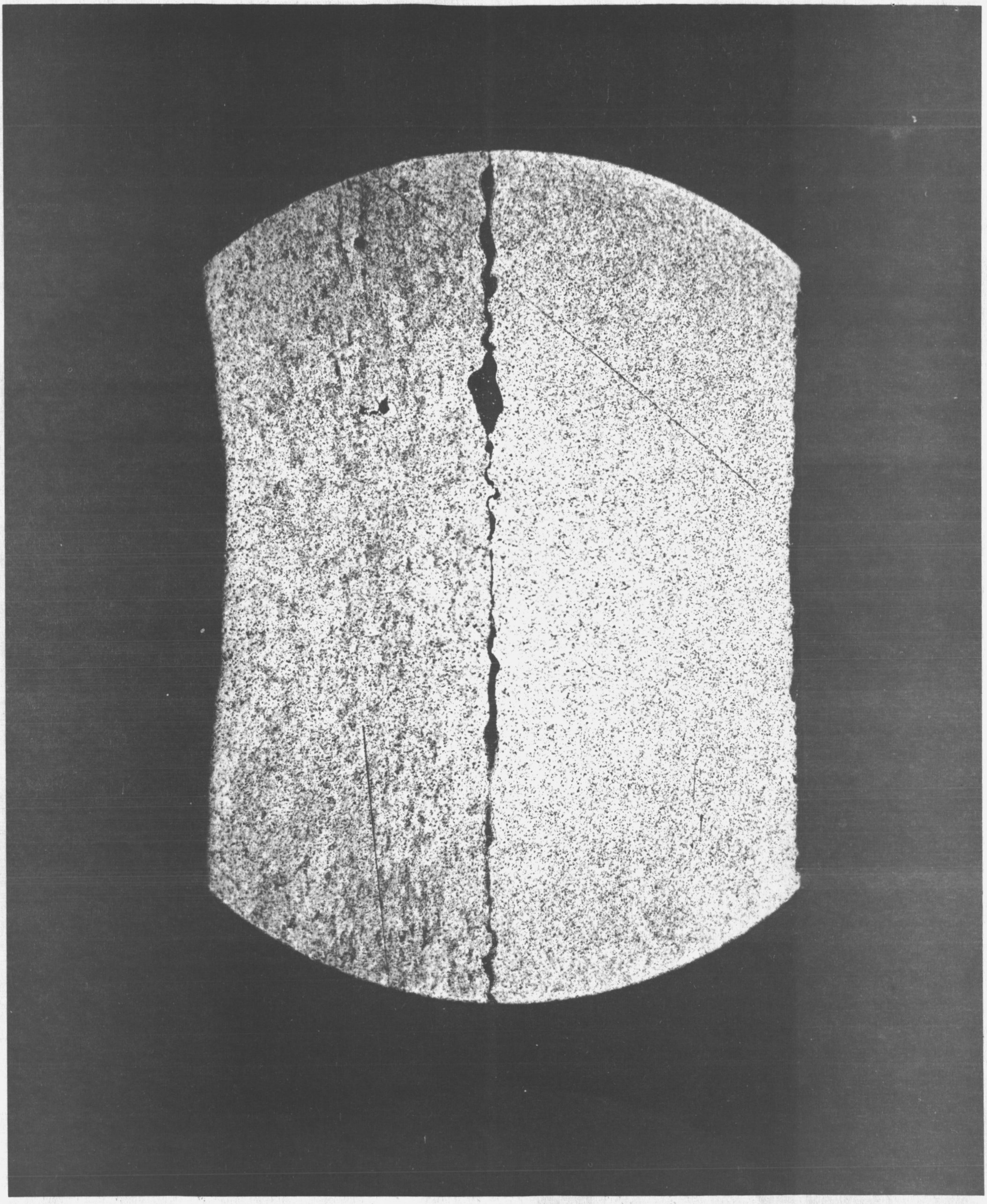


Figure 18. Indentation where Shock Waves Meet.

Section 6

MAGNETIC FORMING

INTRODUCTION

Magnetic forming, while not new, has recently been applied in industry for applications similar to that of forming permanent connections and joints in tubes for leak-tightness. The process involves the application of a rapidly created magnetic field around the work piece with the piece itself the electric conductor.

The rapid creation of this magnetic field produces eddy currents in the work piece which react with the field and produce a significant magnitude of force which repells the work piece from the field producing coil. The forces so produced are generally of very short duration, but can be sufficient to produce permanent deformation at a very high rate. In a sense, one can consider that the eddy currents in the work piece constrict the flux lines from the main coil, and that in their desire to not be so constricted the flux produces a "pressure" on the work piece. A typical level of flux may be 300,000 gauss, producing a "pressure" of about 50,000 pounds per square inch (Ref. 5). Rather than accept that pattern which the coil would normally produce, metal inserts known as "field shapers" can be used to vary flux density and produce a desired pattern of "pressure."

Magneform, a machine designed and marketed by General Dynamics Corporation, employs the magnetic forming principle, and was used throughout this study. By the use of this device, pressure and vacuum tight joints in both similar and dissimilar materials were produced. Relative to the overall requirements of a permanent connector, preliminary information indicated that the process was unique in that it provided a solution to virtually all major problems. For example:

1. The process in no way affected the cleanliness of the end product.
2. The process introduced an increase in joint strength through cold working. Although this may vary with material, the strength factor is essentially always a plus value, allowing an optimum in strength-weight ratio in the joint.
3. The forming pressures and forces tended to be comparable to those of the explosive welding processes, thus they introduce the possibility of effecting a cold weld as well as pressure-deformation relationships (swaging) for sealing.
4. The process can be applied to joining similar and dissimilar metals.
5. While the process depends on the formed material being a conductor, and the efficiency is a function of the resistance of the formed material,

the process can be applied to non-conducting or poor conducting materials provided a good conducting "driver" can be used.

6. The process is capable of being made portable, and requires a minimum of operator training or skill as compared to typical welding processes. With proper dimensional setup and predetermined coil-power setting, the process is essentially independent of any other variables, human or otherwise.

With the foregoing considerations in mind, the program described in the remainder of this section was instituted in an effort to determine whether the magnetic forming process could be applied to the task of permanent connector fabrication of in-place assemblies.

In addition to the tests performed on tube connections, several tests were made in an attempt to improve the characteristics of the magnetic forming machine.

MAGNETIC FORMING TEST SUMMARY

The primary aim of all tests performed was to effect a pressure seal between a tube and an insert. When two such connections can be successfully made, a tube-to-tube junction is formed. Much like in the explosive forming operation, the insert performs the function of supporting the high stresses required to make the joint and acts as one of the seal elements.

A typical joint configuration is shown in Figure 19 and 20. It is recognized that this joint presents a line restriction. However, this restriction must not be construed as part of the final joint design because the joint configuration tested was merely a convenient mechanism to evaluate the sealing capability of the magnetic forming process and to establish procedures and parameters.

Aluminum materials were the primary materials used in all tests. Both 6061-T6 (hard) and 3003-H14 (soft) were used as tube elements to provide a comparison between the hardness of tube materials. Most inserts were made from 2024 variety aluminum; while a limited number employed the softer 1100 series aluminum. Two inch and three-eights inch outside diameter tubing were chosen as the test sizes so that comparison could be made. Early in the program, however, tests were concentrated on use of the three-eights size. This was prompted by the fact that the 6000 joule maximum power output was able to create enough deformation to make satisfactory joints approximately that size.

One test series used brass for its tube material and an aluminum sleeve as the "driver". Reasons for this choice will become apparent in the following test summaries.

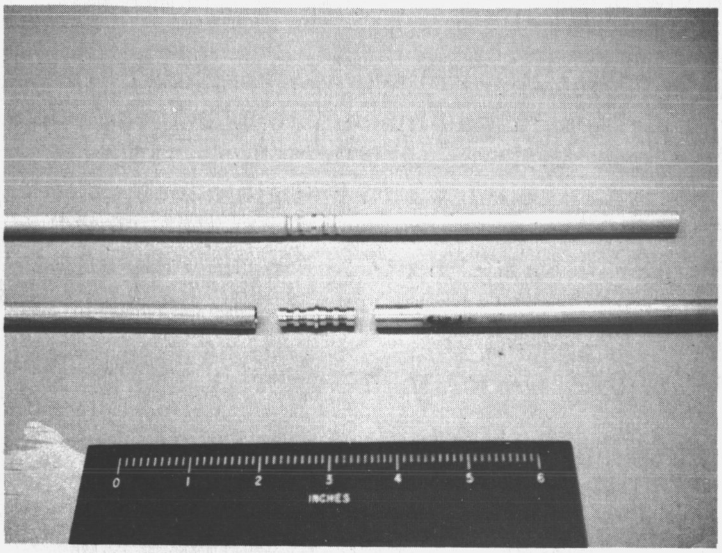


Figure 19. Lower Portion Shows Elements of Magnetically Swaged Connector. Upper Portion Illustrates Completed Connection (3/8 inch Outside Diameter Tubing, 3003-H-14 Aluminum; 2024-T4 Union).

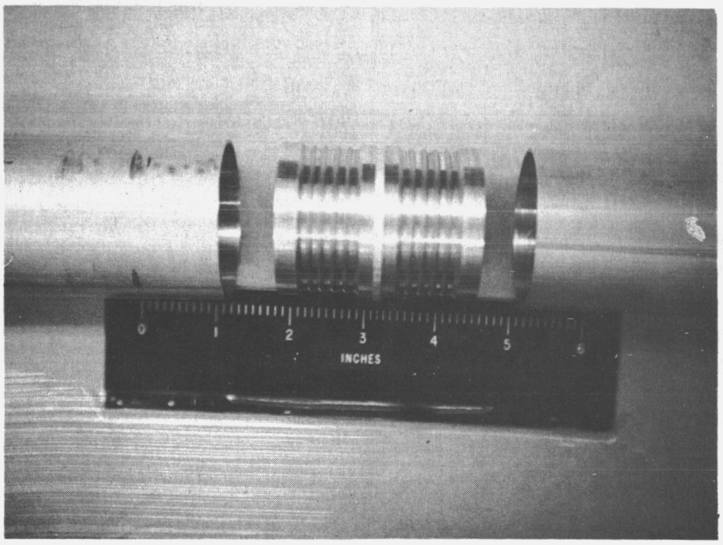


Figure 20. Elements of 2 inch Connector for Magnetic Swaging (Tubing - 3003-H-14 Aluminum; Union 2024-T4).

For the finished joint shown in Figure 21 and 22, a mass spectrometer check with internal vacuum was made and no evidence of a leakage was found. To test the joints sensitivity to vibration, the sample was mounted and vibrated at its natural frequency at a 200 g's acceleration level for approximately 15 minutes. A second leak check showed the joint to be still leak-tight. However, leakage did occur in the tube at the point of mounting and at one of the tube convolutions adjacent to the seal section. Both leaks were attributed to fatigue failure at these points. A second connector with the same insert configuration was made and subjected to the following tests:

1. A one atmosphere leak test (atmospheric pressure to a vacuum); no measurable leak was in evidence.
2. The system was pressurized at 2000 psi with helium for a period of 20 hours. Again, no measurable leak (less than 10^{-7} atm cc/sec)
3. The connector was vibrated for 20 minutes in a manner such that 200 g's loading existed on the connector.
4. Successive vacuum and pressure leak checks were performed, again yielding no measurable leaks.

Encouraged by these successes, the test program was now directed toward the collection of design information concerning this technique. Very soon, however, two serious problems arose. First, a lack of circumferential informity of the tubes' deformation in the joint at the completion of the forming process was found (See Figures 21 and 22). Secondly, it was discovered that this forming technique allowed a certain degree of elastic springback in the deformed material. The elastic springback, in turn, caused separation of the mated parts so that a seal was not effected. This phenomenon has been previously discussed in Section 5 "Explosive Forming" of this volume and is illustrated in Figure 4 which shows the cross-section of an explosively formed joint.

Several different experiments throughout the program were conducted with the magnetic forming machine and specially fabricated tube and insert process in order to overcome the above shortcomings.

In order for the force field to be concentrated over a small length (measured longitudinally), a shaper is fitted into a work coil. The shaper, made from beryllium copper, has the function of concentrating the force over an extremely small length. However, in order that this shaper will not contain a single loop coil, a slit is radially cut across its thickness. At this slit, however, the force field is not the same as elsewhere about the periphery. This problem is inherent when a shaper is used and thus the question arose as to whether this problem could be sufficiently reduced by proper sizing of the shaper. Three different techniques had been considered to reduce the effects of this phenomenon. First, a reduction in the width of the slit was tried. As the slit becomes narrower the diminution in the force is limited to a smaller part of the periphery. The first shaper coil had a

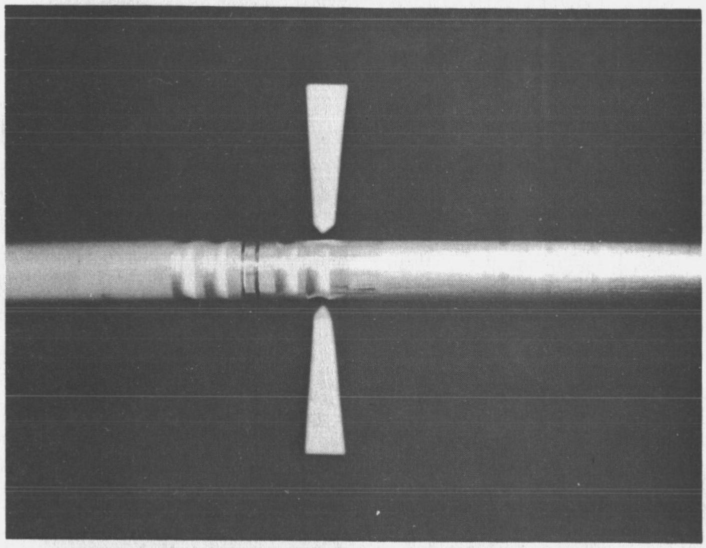


Figure 21. Uneven Depth of Draw Due to Width of Split in Shaper.

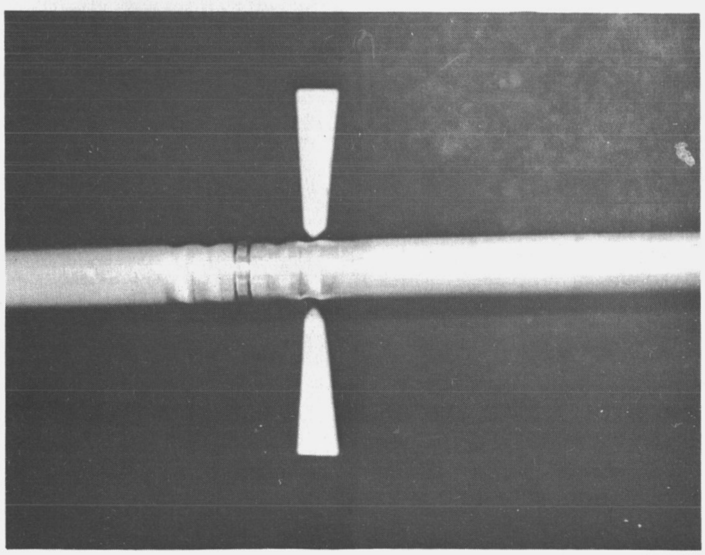


Figure 22. Uniform Depth of Draw; Plane of Photo 90^{o} from Plane of Shaper Split.

0.065 inch slit while the following shaper coil was machined with a slit of only 0.011 inch. Initial tests conducted with the second shaper did not show a significant amount of improvement in the circumferential uniformity of tube collapse. These tests were conducted on three-eights inch aluminum tubing. The results of this experiment were not encouraging.

A second means of reducing the singularity effect was to increase the clearance between the outside diameter of the tube and the inside diameter of the shaper. While this technique inherently reduces the force experienced by the tubing, it tends to wash out any deviations in the force field. Initial tests were made with the clearance between the outside diameter of the tube and the inside diameter of the shaper being equal to the slit width in the shaper. Additional tests were conducted with ratios of the tube-shaper clearance to shaper slit being 1 to 1, 2 to 1, 3 to 1, and 3.5 to 11. These tests gave no significant increase in quality of the joint.

The technique of employing the magnetic forming process twice on the same connector was also tried in several samples. While initial test of this technique showed some tendency to separate surfaces already mated, later tests illustrated that some reduction in leakage rate is possible. The first forming operation usually resulted in non-uniform collapse of the tube into the insert groove. The tubes were leak tested at one atmosphere pressure differential and then re-swaged by the magnetic forming process with the tubes rotated 180° with respect to the shaper slit from the first forming operation. A second one atmosphere pressure differential leak test performed showed a definite improvement in leakage rates in the case where 6061-T6 aluminum tubes were used. Second leak tests in cases where 3003-H14 aluminum tubes were used proved inconclusive. Visual inspection of the difference in the amount of deformation caused by the second magnetic forming process yielded similar results. Overall, it was noted that the 3003-H14 tubes were not as highly affected as those of 6061-T6 aluminum

Further testing in the program embodied a concerted effort directed toward the design and testing of various insert and connector configurations. This appeared necessary in light of the success derived from the initial connections made and the apparent lack of knowledge of this process as applied to connectors in general. Since many samples can be magnetically formed within an hour's machine time, several samples of different varieties of insert configurations can be economically made and much valauble design data derived. Many configurations were designed to increase a certain element of understanding of the process while others were developed in order to take advantage of the knowledge gained.

Initial Connector Insert Design

The configuration (Figures 19, 21, and 22) was successful. Subsequent X-rays (Figures 23 and 24) indicated lack of deformation uniformity and

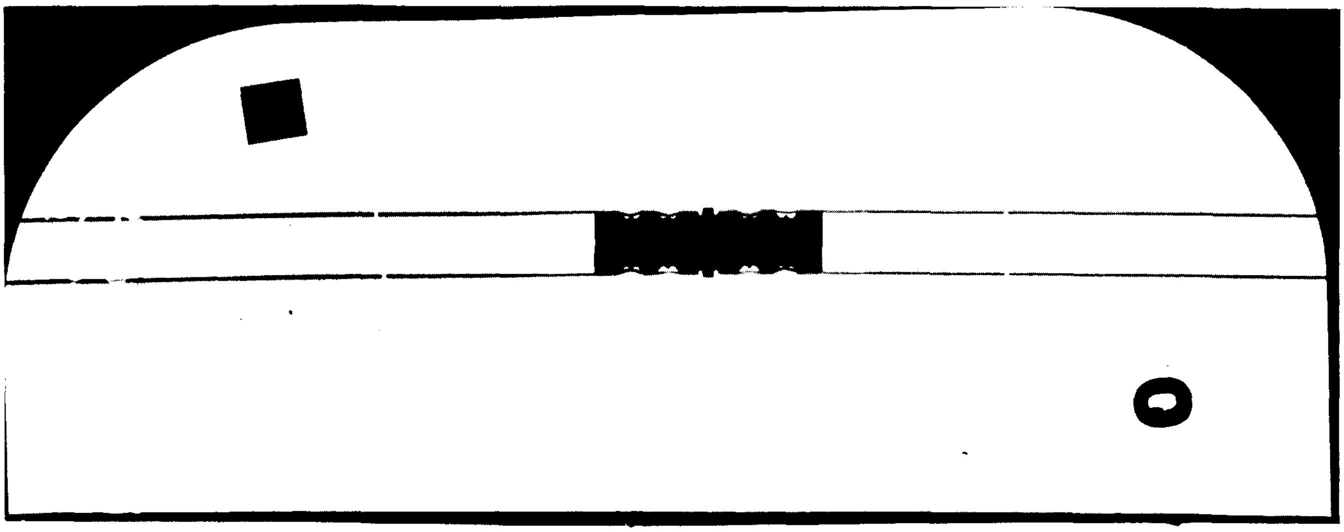


Figure 23. X-Ray of Magnetic Formed Permanent Connector. Note Variation in Tube Deformation. This Connector has been Successfully Leak Tested.

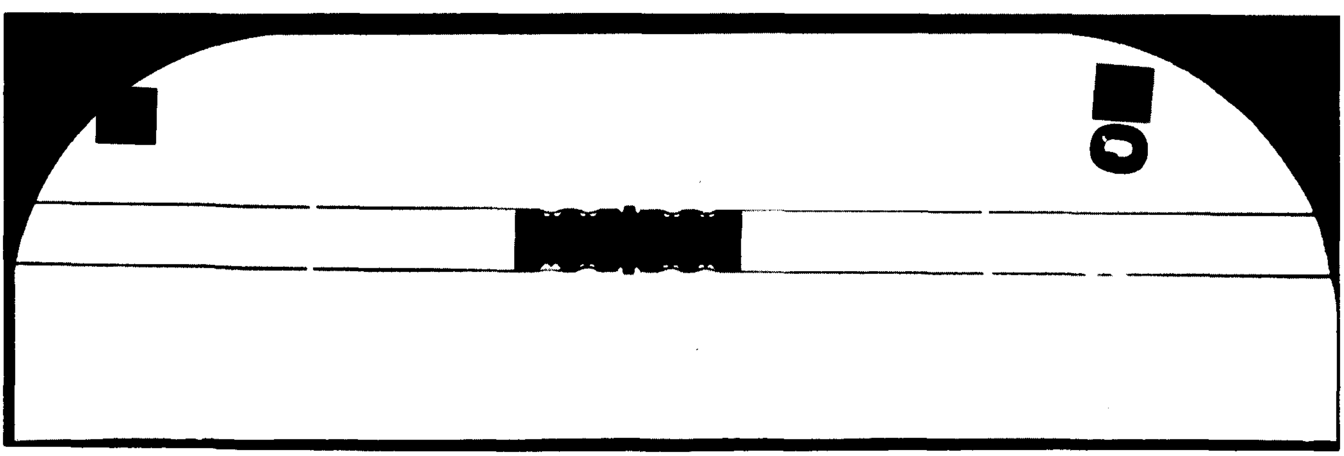


Figure 24. X-Ray of Same Connector as in Figure 23, Rotated 90^o.

lack of sealing at the knife edges. Any seal that occurred must exist at the start of the trough adjacent to the knife edge. Results of these tests were already discussed.

Gap Depth and Width Series

This series was designed to obtain knowledge concerning the depth of deformation of the tube into various widths of grooves. In addition, several tests were made with constant width gaps but with varying depth. Gap lengths were incrementally varied from two to eight times the 0.035 inch tube wall thickness. Both 6061-T6 and 3003-H14 tube materials were used (Sees X-ray Figures 25, 26, and 27). These tests were designed to provide information relative to design of upcoming knife edge and springback insert configuration tests. As expected, the width of the groove increased, as did the depth to which the tube deformed.

SB Series

This test series was designed to overcome the tube's springback tendency. Inserts were made with varying wall thicknesses to determine which ones reacted best. Both 6061-T6 and 3003-H14 tubes were used (See Figure 28). Insert thicknesses were 20, 30, 60, and 90 thousandths of an inch. Of the eight samples tested, vacuum leak tests showed that the best seals were made with thinner walled inserts.

KE Series

This knife edge series was performed with inserts using various heights of annular knife edges designed to "bite" into the deformed tube. Even though non-uniform tube deformation was shown to be a problem, it was felt that successful connections could be derived with inserts designed from data gained in the varying gap tests. Eight samples were tested with 6061-T6 tubes. Three knife edges were too short to make contact with the tube. However, two of the highest ones resulted in seals of the order of 10^{-6} atm cc/sec (See Figure 29).

Free End FE Series

This series of tests used an insert designed so that the end of the tube was deformed into the insert groove. Eight samples (four each with both tube materials) were vacuum tested. Leaks ranged from 10^{-2} atm cc/sec to 10^{-8} atm cc/sec. The two best (both with 6061-T6 tubes) were pressued tested. One showed no leakage at 2000 psi or 24 hours. The other leaked at the 1800 psi level (See Figure 30 insert).

Repeatability and Surface Finish (SS) Series

At this point in the program, it was decided to test the repeatability of the magnetic forming process. The same basic configuration as that used for

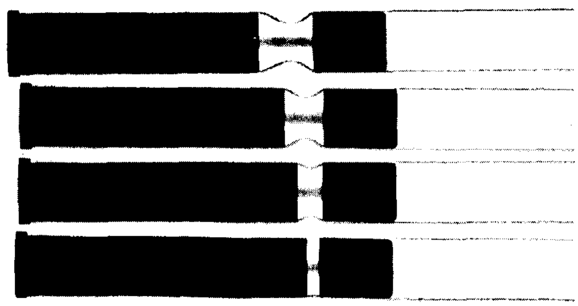


Figure 25. 6061-T6 Aluminum Tube Deformation as a Function of Gap Length for Constant Magnetic Field Strength. Insert is 2024-T3 Aluminum. Gaps Range from 2x, 4x, 6x, and 8x of the Tube Wall Thickness. Tube Wall Thickness is 0.035 inch.

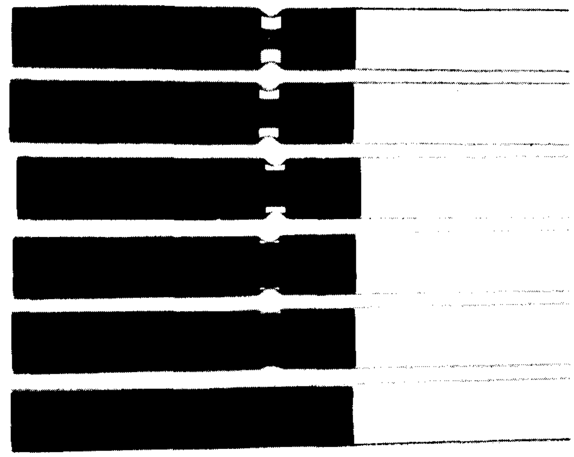


Figure 26. 3003-HI4 Aluminum Tube Deformation with Varying Gap Depth. 2024-T3 Aluminum Inserts. Magnetic Field Strength not Varied. Gap Length is 3x Tube Wall Thickness. Tube Wall Thickness is 0.035 inch Depth of Gap - 0x, 1x, 1.5x, 2x, 2.5x Tube Wall Thickness.

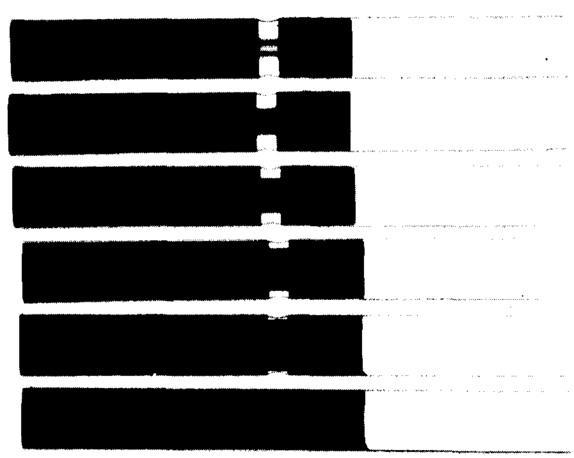


Figure 27. 6061-T6 Aluminum Tube Deformation with Varying Gap Depth. 2024-T3 Aluminum Inserts. Magnetic Field Strength not Varied. Gap Length is 3x Tube Wall Thickness. Tube Wall Thickness is 0.035 inch Depth of Gap - 0x, 1x, 1.5x, 2x, 2.5x Tube Wall Thickness.

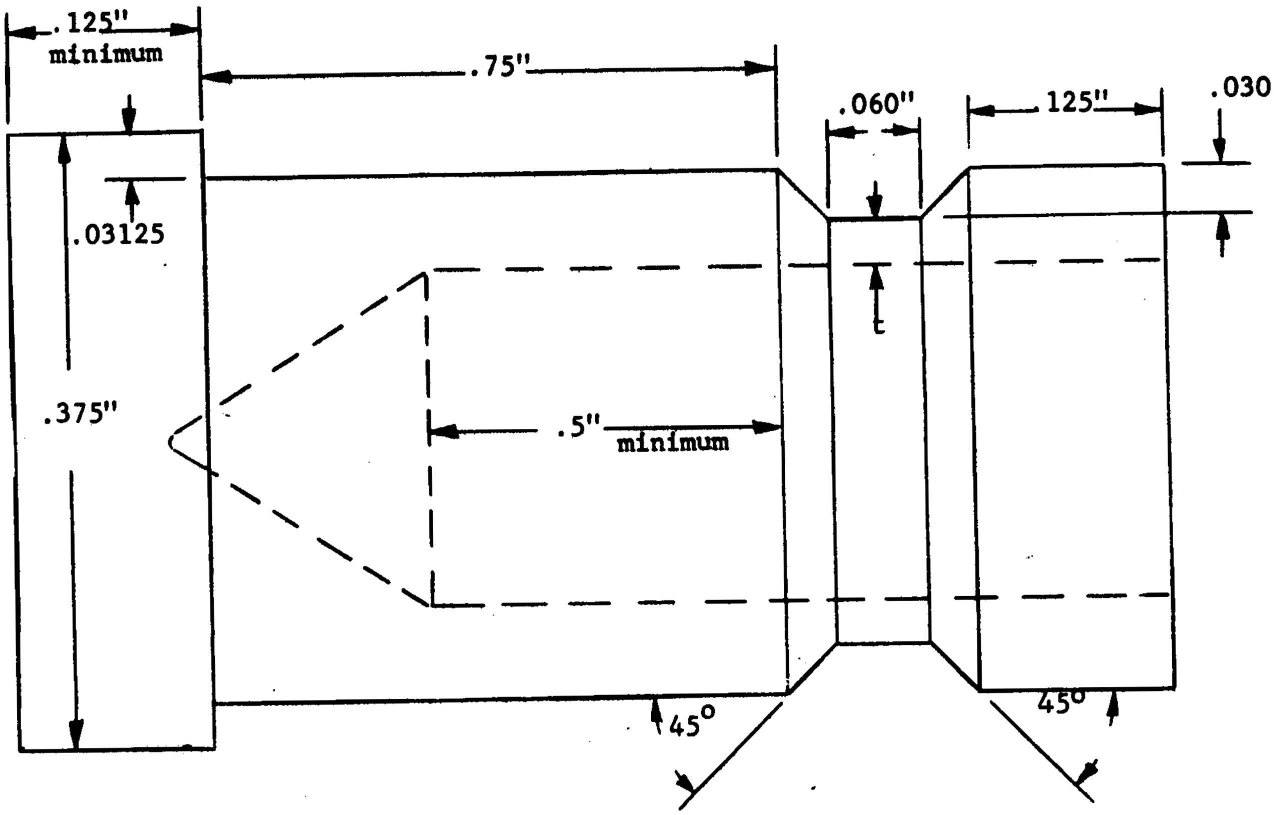
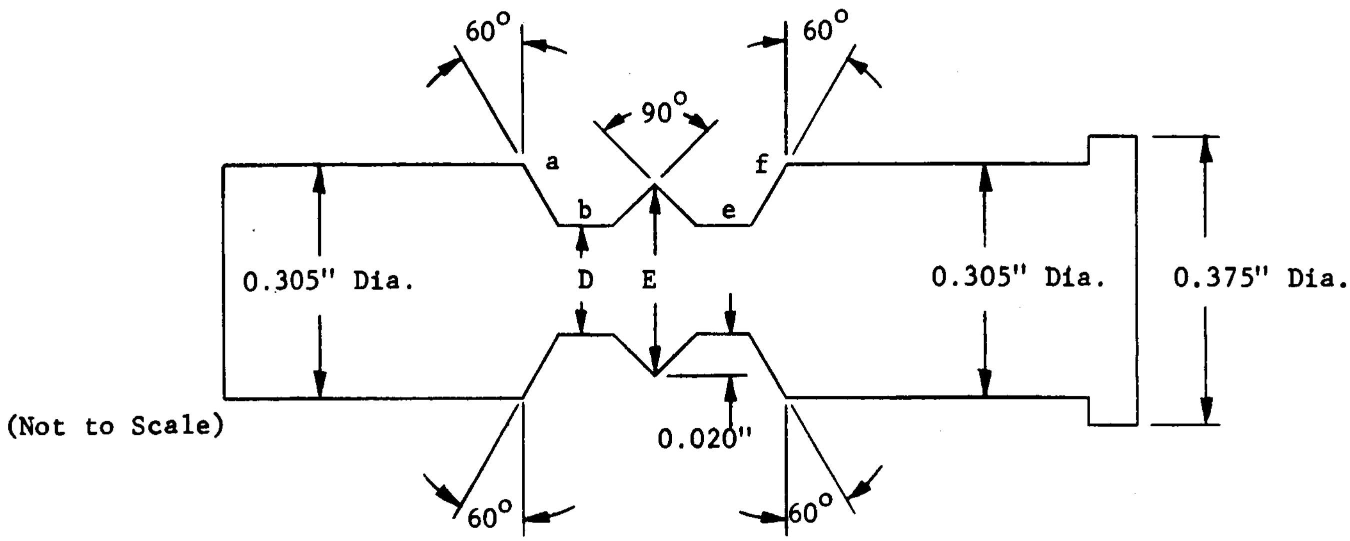
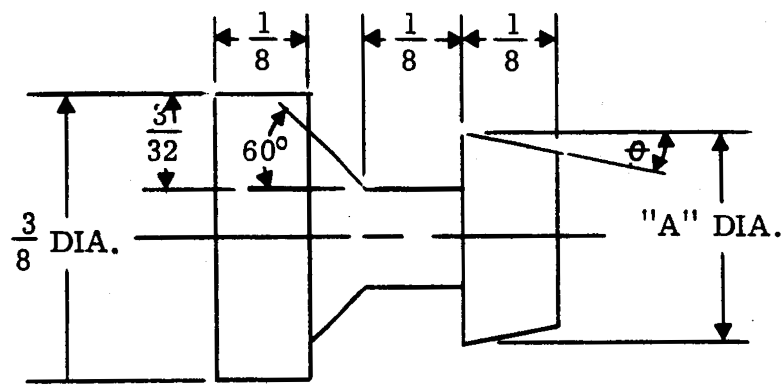


Figure 28. SB Series Insert



Sample	D	E
1	0.197"	0.237"
2	0.207"	0.247"
3	0.217"	0.257"
4	0.227"	0.267"
5	0.237"	0.277"
6	0.247"	0.257"
7	0.257"	0.297"
8	0.265"	0.305"

Figure 29. Knife Edge Series Insert



"A" DIA. Snug Fit Inside

$\frac{3}{8}$" O. D. Tube

Figure 30. Free End Series Insert

the very first successful inserts was employed but without the knife edges since X-rays showed them not to be beneficial (See Figure 31). Also, four out of the eleven inserts were lightly sand blasted to test the effect of the different surface finishes. The finished joint is shown in Figure 32. Random pressure levels at which leakage occurred after successful vacuum tests showed the inconsistency of the technique. Excessive leakage occurred at levels ranging from 0 to 2000 psi. The different surface finished seemed not to effect the results.

SS Series Tensile Tests

Two of the SS series test connectors were tensile tested and showed strengths in excess of the strength of tube material. (Approximately 45,000 psi).

The following three insert configurations were designed to improve sealability at the point where the tube material begins to deform into the groove. X-rays of prior successful connections showed this area to be where sealability occurred

SP Series

This insert configuration (See Figure 33) was designed with a knife edge at the start of the groove. The idea was to take advantage of the shear action caused by the tubes' deformation. Relative motion between tube and insert would cause a "biting-in" action. Of the three samples made, each with both kinds of tubing, all showed excellent sealability in the vacuum test (leaks beyond the range of the equipment), but all three of those pressure tested leaked at low internal pressures, ranging from 5 to 150 psi.

SH Series

This insert (See Figure 34) was designed to act as an annular centilever to overcome the tubes' spring-back tendency. The high degree of flexibility at the tube and insert junction coupled with its "bite-in" characteristic was tested in six samples, three each with the soft and hard tubing. All showed good sealability (leaks between 10^{-5} atm cc/sec to undetectable) in the vacuum check, but the one sample that was pressure tested leaked at 5 psi.

SC Series

Like the SH series, this insert (See Figure 35) was supposed to provide a spring action but with increased stiffness. Again, six samples were made and showed excellent vacuum sealability beyond the range of detection. On pressurizing them, however, all leaked at low pressures ranging from 5 to 400 psi. The remaining test series involved efforts to learn more about the magnetic process and its characteristics and to check the various ideas formulated from the foregoing tests.

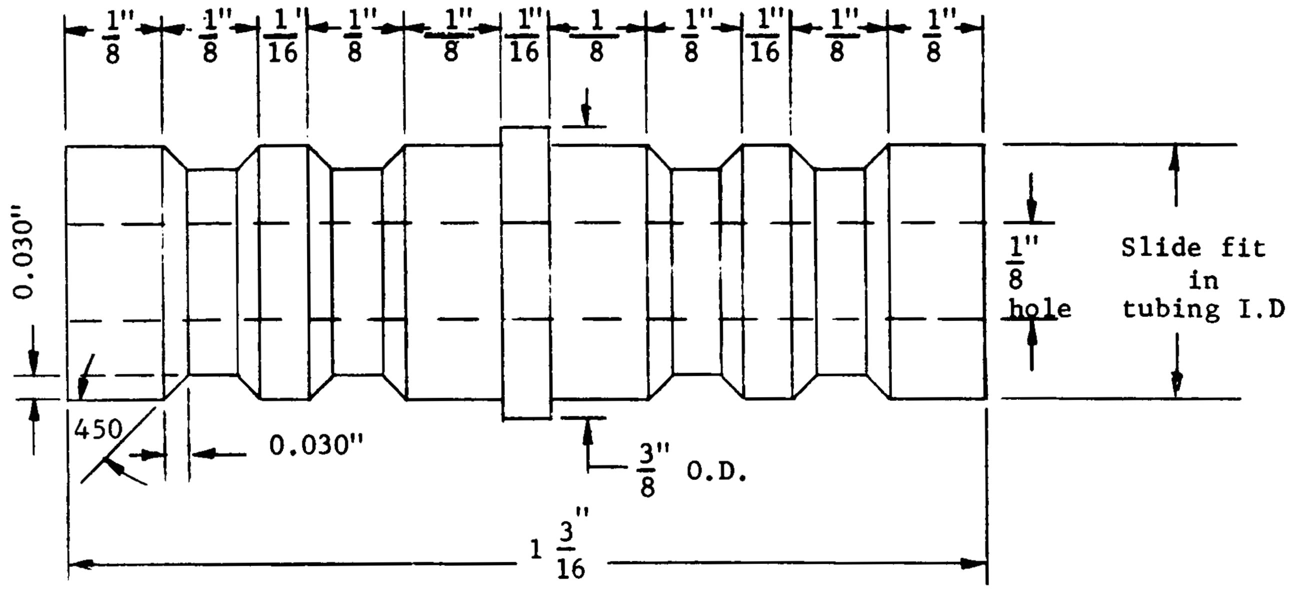


Figure 31. SS Series Insert Geometry

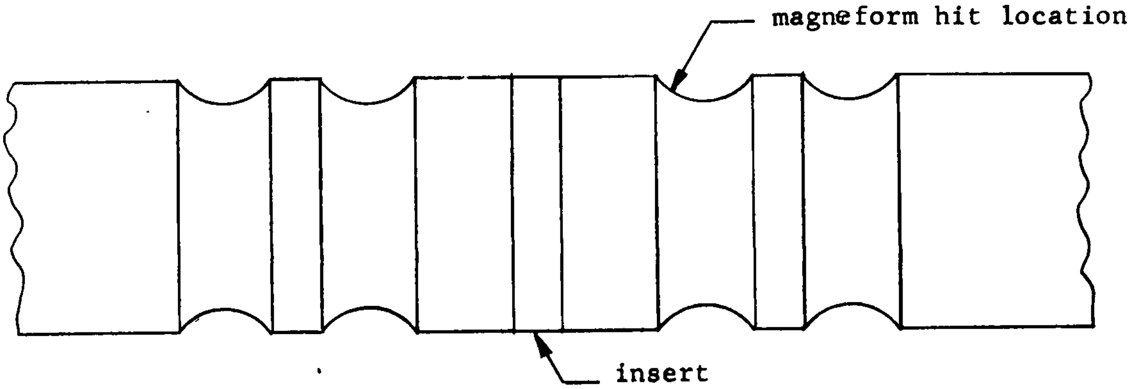


Figure 32. Final Connector Shape

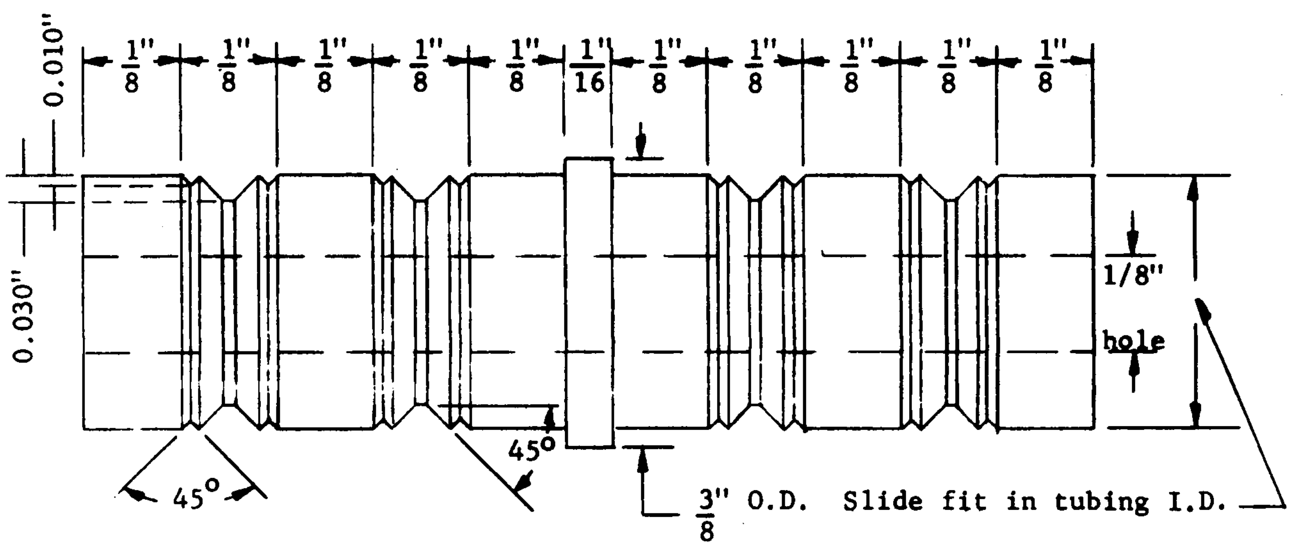


Figure 33. SP Series Insert Geometry

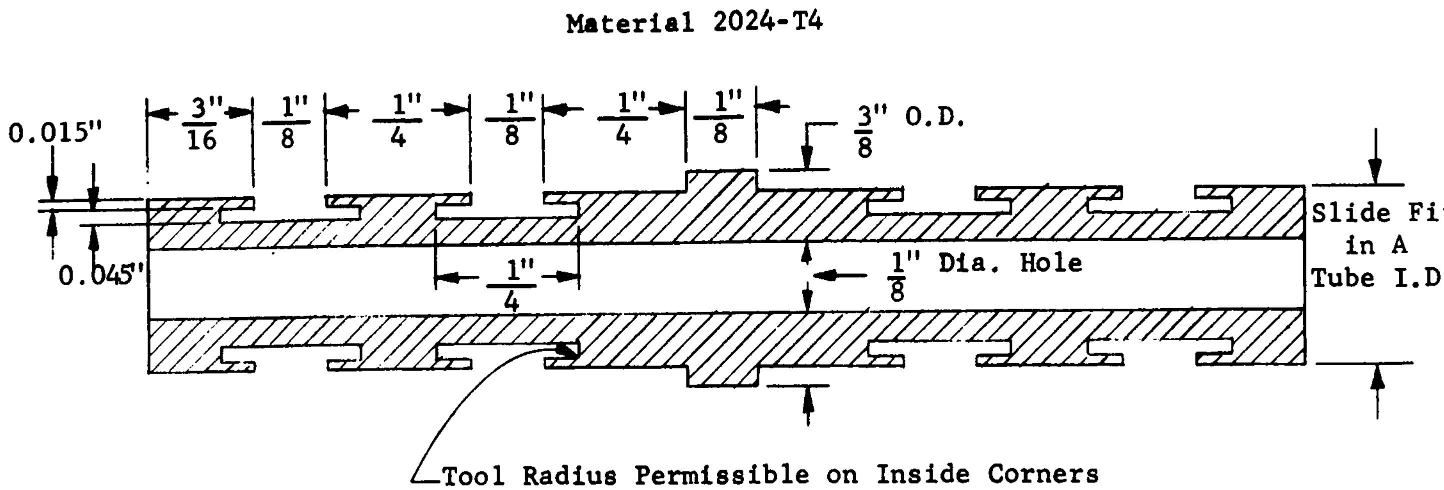


Figure 34. SH Series Insert Geometry

Material 2024-T4

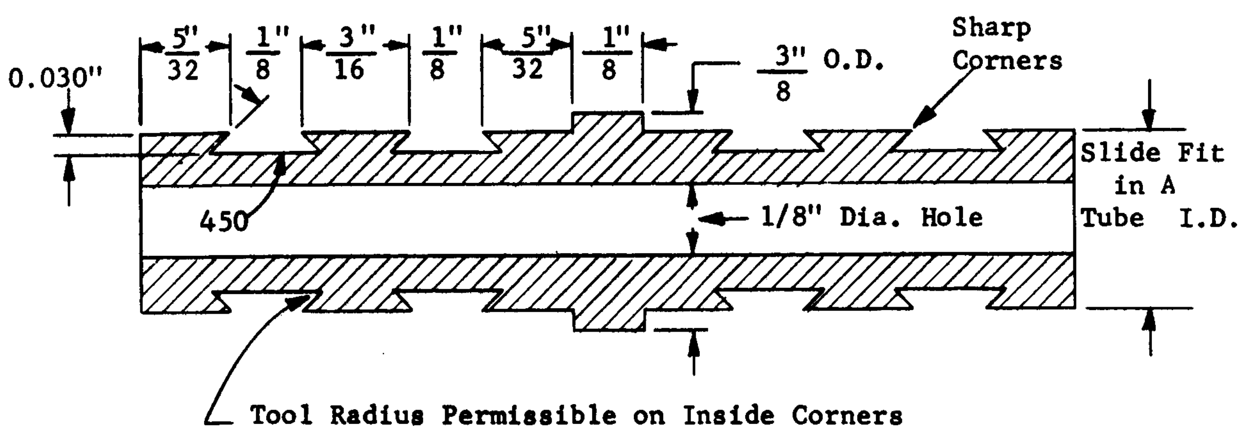


Figure 35. SC Series Insert Geometry

SJ Series

Several samples were made to test the sealability offered by the use of solft filler materials in the seal grooves. Five samples were made with brass materials for tubes and insert (See Figure 36). The inboard grooves were filled with solder and shaped. The outboard grooves were used as positioners with the first tube deformations made at those locations. The brass tubes were machined down to allow 0.003 inches of solder coating of their inside diameter and placement of aluminum "driver" sleeves required for the process. It was found that aluminum reacts better to this kind of forming operation, creating more force at the insert. All samples made showed low leakage in a vacuum test, the highest 10^{-6} atm cc/sec.

R Series

The inserts shown in Figure 37 were designed with ramped sides of the inboard grooves. The deformation of the ends of the tubes down the ramp was to instigate sealing due to the relative motions involved. Springback was to be obviated by the inability of the tube to travel back up the ramp. The outboard groove, like the SJ series, was for positioning only. Tubes were of 6061-T6 tubing and inserts were 1100-F aluminum material. A cold weld was sought between the hard and soft materials. All Five samples made showed excellent vacuum sealability (ranging from 10^{-5} atm cc/sec and lower) but low pressure sealing. The highest pressure level attained was 30 psi; however, most samples began to leak in the neighborhood of 0 psi.

Tube-to-tube Configuration Series

The final attempt at making a tube joint was done with the configuration shown in Figure 38. The idea was to create relative motions between the tube sections while they were deformed into the groove. All of the materials were aluminum. The outer tube was 3003-H14, the inner tube 1100-F aluminum, and the insert 2024-T4. Of the three samples made, all showed very high vacuum test leakages in the neighborhood of 10^{-1} atm-cc/sec. Deformations at the maximum (6000 joule) power setting of the magnetic forming machine were disappointingly low.

A departure from the tube insert configuration was that shown in Figure 39. It represents a flange joint designed to take advantage of high deformation resulting from flat coil magnetic forces. Sealing was to occur at the tongue and groove type of annular rings. In addition to this configuration, flat plates were also tried with no surface deviations. Both showed disappointing results. The first cracked at the base due to excessive deformation; the second showed no connection at all, a manual pull resulting in separation of the plates. (See Figures 40 and 41).

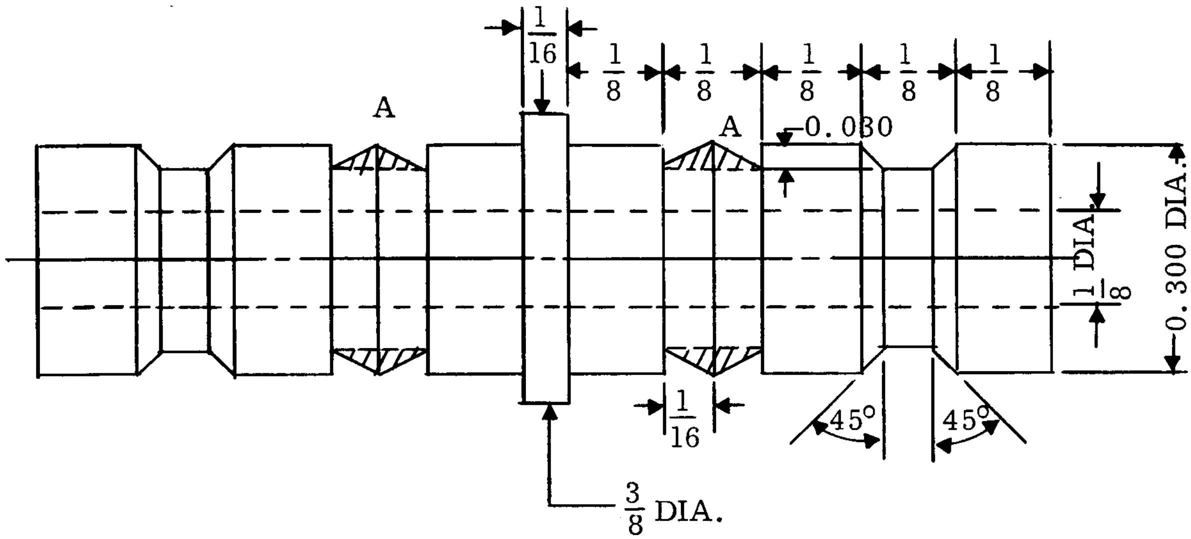


Figure 36. SJ Series Insert

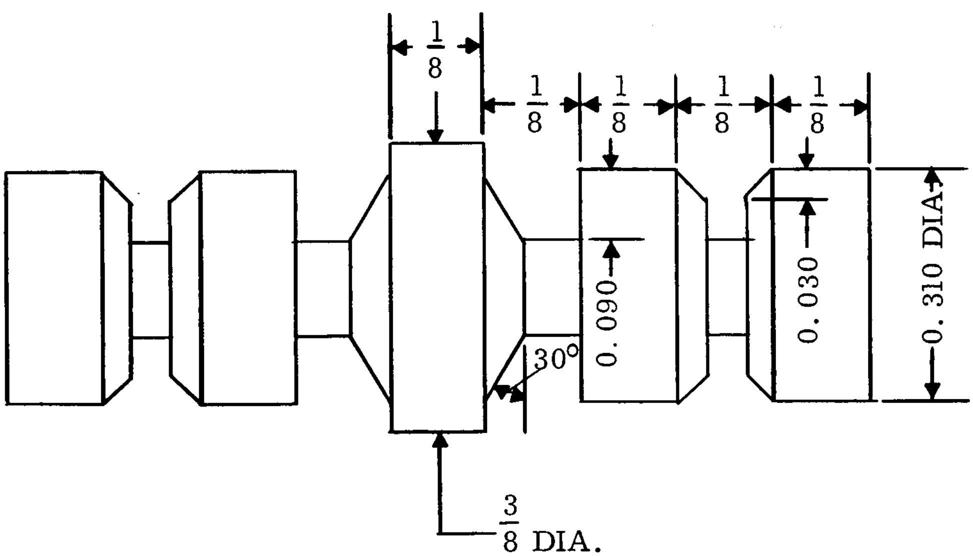


Figure 37. R Series Insert

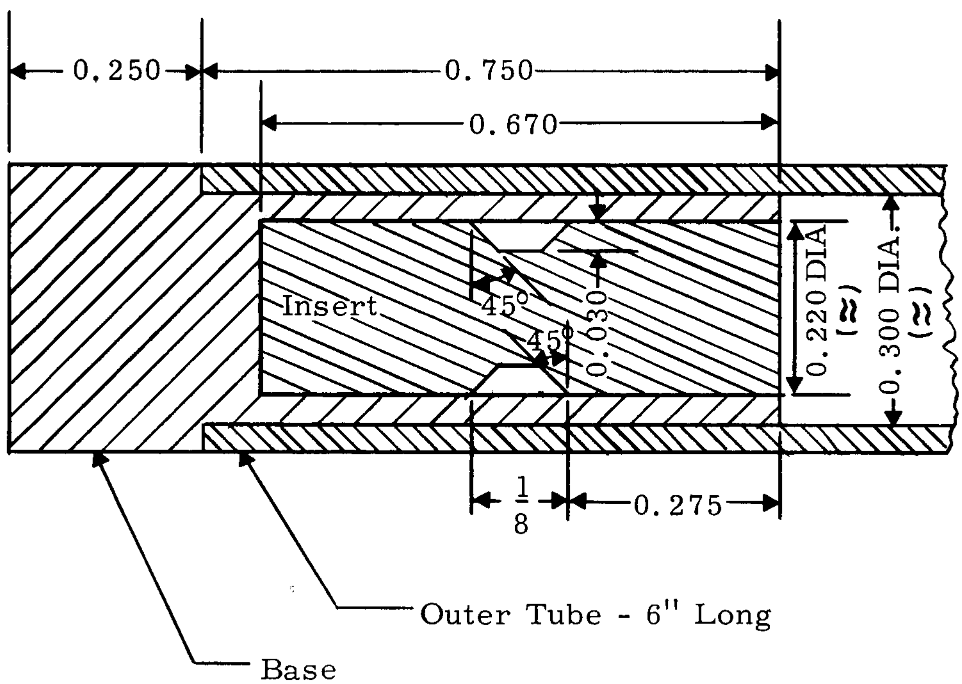


Figure 38. Tube to Tube Configurations

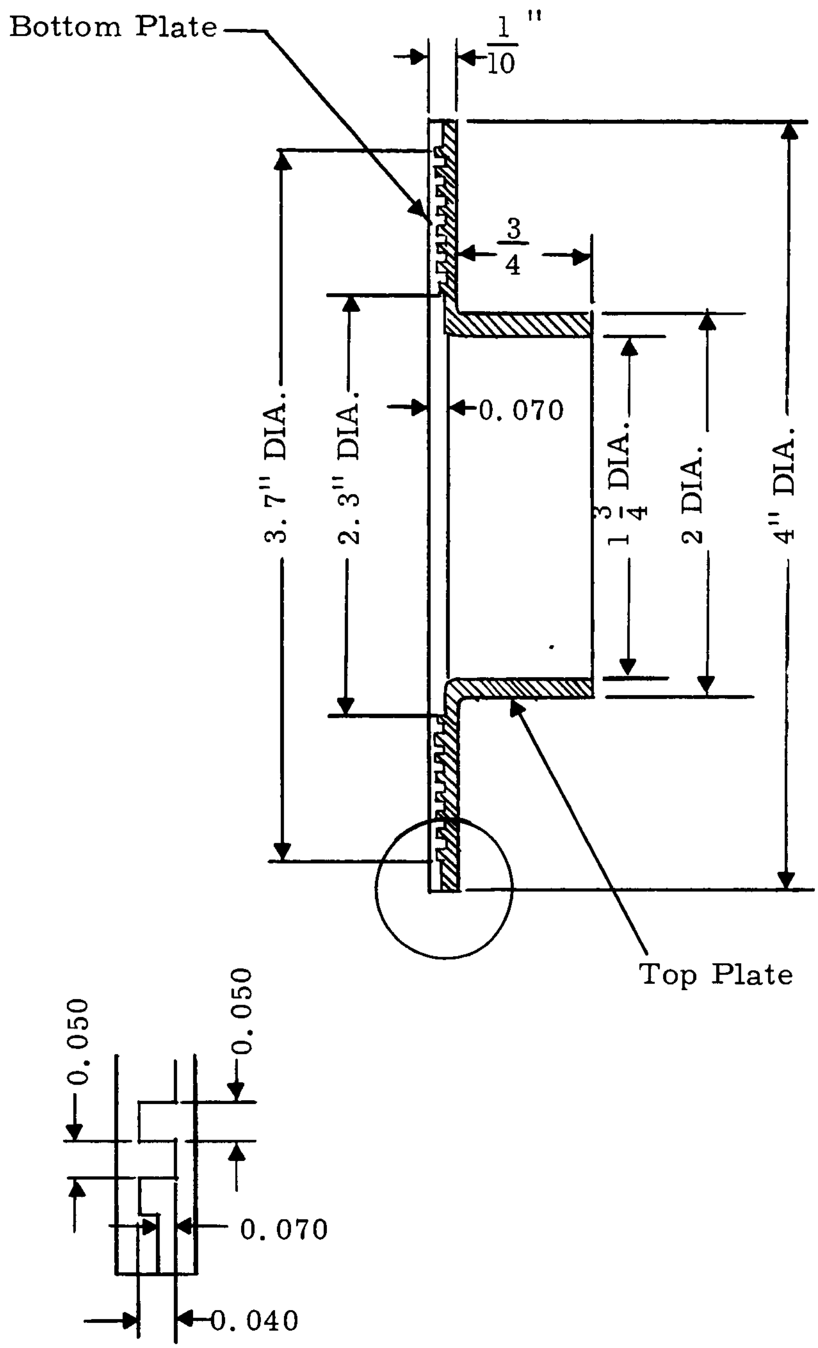


Figure 39. Plate to Plate Joint

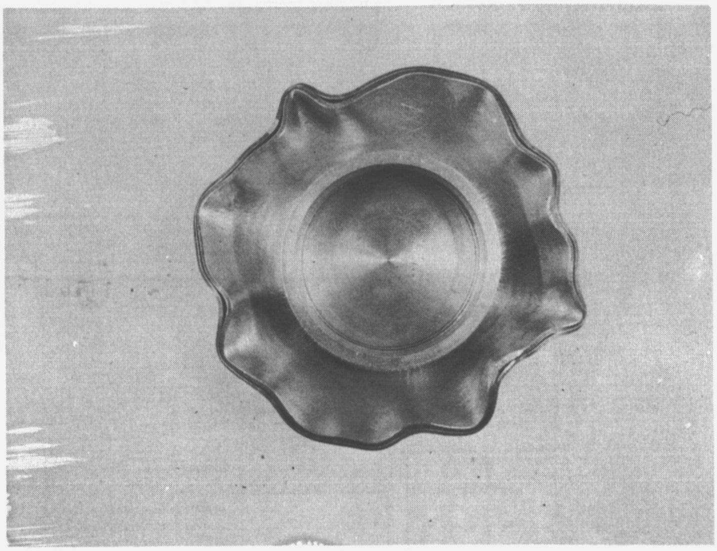


Figure 40. Top View of Magneform Assembly Shown in Figure 39.

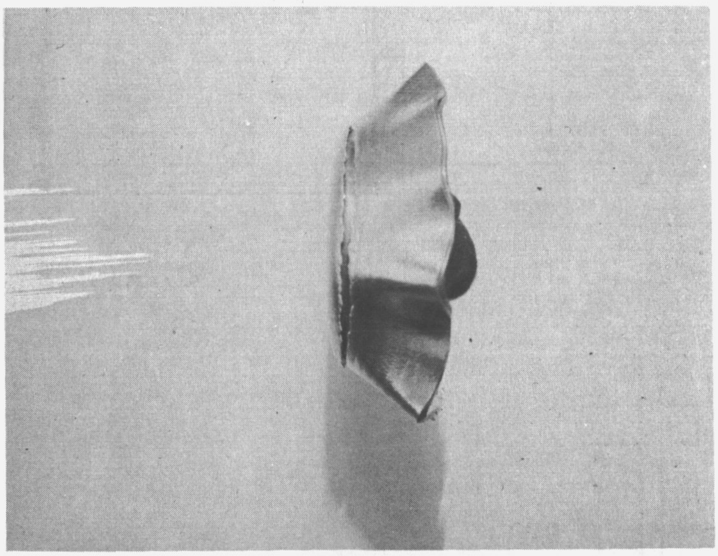


Figure 41. Side View of the Mangeform Assembly Shown in Figure 39.

Section 7

ADHESIVE BONDING TECHNIQUES

INTRODUCTION

The technique of using adhesives to bond tubes and ducts has many present day applications in aircraft, missiles, and spacecraft. To date, adhesive joints with tensile strengths as high as 15,000 psi have been obtained with aluminum and adhesives like epoxy resins (for instance, Araldite AN-100 and Epon VI). Therefore, for duct joint applications, where no large bonding areas are available, tapered joints can be employed to increase the strength efficiency of the bond. The typical tube angles which should be expected should be within 5 to 10 degrees. Thus, with these facts in mind, this technique was explored as a possible method of making duct joints.

DESIGN CONSIDERATIONS

If the angle of the taper is called α (See Figure 42) the ratio of the cross-sectional area of the tube to the surface area of the taper is:

$$\frac{A\ \text{adhesive}}{A\ \text{tube}} = \frac{1}{\sin\alpha}$$

The angle α itself can be determined by the simple assumption that the joint should have the same strength as the pipe and then also:

$$\frac{\sigma\ \text{tube}}{\tau\ \text{adhesive}} = \frac{1}{\sin\alpha} \quad (\text{for small } \alpha)$$

For different angles this factor becomes:

α	σtube/τ adhesive
5^{o}	11.47
7^{o}	8.206
8^{o}	7.185
10^{o}	5.759

This is only a theoretical factor based on the geometry and neglects the facts that the edges are not perfectly sharp and that the adhesive line has a certain thickness. However, this calculation does show that an adhesive with strength as low as 10 percent that of the pipe material could produce adequate joints.

Adhesive joints which might not be strong enough for some structural purposes could very easily be supported mechanically with some lightweight equipment and still take advantage of the leak-tightness of adhesive bonds.

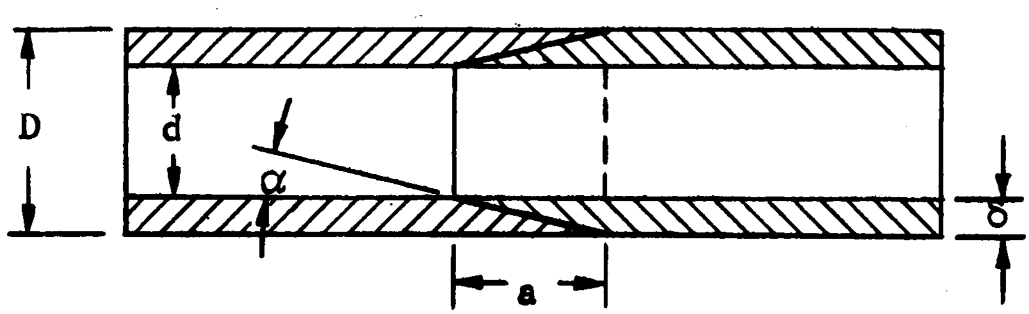


Figure 42. Typical Bonding Geometry

In all cases the adhesive was cured at room temperature overnight and then for two hours at 176°F.

Series "T" was made from different tube ends with plain tapered joints but different angles of taper. All samples proved to be leak-tight; however, only four of them could be pressure checked because of the dimensions of the vacuum chamber. During the test the tubes were pressed between two sealing end caps in order to pressurize them. Table 1 gives the results of the series T tests.

Table 1

SERIES T TEST RESULTS

	Characteristics	Vacuum Test	Inside Pressure	Leakage (atm cc/sec)
T-1	1" O.D. x. 065"; 5° taper	No leak	1000 psi	2×10^{-8}
T-2	1" O.D. x. 065"; 8° taper	No leak	1000 psi	No leak
T-3	1" O.D. x. 065"; 10° taper	No leak	375 psi	1×10^{-8}
T-4	3/4" O.D. x. 065"; 8° taper	No leak	1000 psi	No leak

Series "J" was made of 3/4 inch outside diameter x 0. 095 inch tubing. Instead of plain tapered joints, the male pieces had a machined-in shoulder to adjust different film thicknesses of the adhesive (1/64, 1/32, and 3/64). Samples of this series were run in a rotating beam fatigue testing machine. The eccentricity of the pieces made it impossible to adequately test most of them. However, two samples were loaded with 40 and 60 in-lbs respectively, and run for 100,000 cycles without failure. Further, when these joints were vacuum tested, they both proved to be leak-tight.

As all the plain tapered joints gave better results, a third series "R" was made having a 10 degree angle and using the sample epoxy resin but with different filler ratios. Talc was used as filler material. Samples were made with straight tapers from 3/4 inch outside diameter x 0. 095 inch tubing.

Out of the 25 samples, all were leak-tight except one which showed a small leak (1×10^{-9} atm cc/sec) after 1/2 hour. All samples were then subjected to an extended time leakage test of less than one hour. No other leaks were found. After this preliminary check, 21 of the samples were subjected to the following tests:

- Five samples pull-tested for their tensile strength.
- Eight samples thermocycle tested between -67 and +185°F.

  Three of the eight samples pulled for tensile strength at room temperature.

  Five of the eight samples thermocycled between -295 and +185°F.

  Two of the five samples pulled for tensile strength at room temperature. The final three samples pulled for tensile strength at -295°F.
- Eight samples vibrated.

The results of the five tensile tests are listed in Table 2. For sample Numbers 1, 3, 4, and 5, an average area of the samples were used. For sample Number 2 the area for the specific sample was employed.

Table 2

TENSILE TEST RESULTS

No.	Load (lbs.)	Average Area (in^2)	Tensile Strength (psi)
1	3,300	0.820	4,020
2	4,000	0.775	5,150
3	3,670	0.820	4,470
4	3,210	0.820	3,920
5	3,740	0.820	4,560

The thermocycling tests were run according to specification MIL-STD-202A Method 102A, test condition D_1, five cycles. Each cycle had four steps and the results are listed in Table 3.

Table 3

THERMOCYCLING TEST SEQUENCE

Step	Minutes at °F.	
1	30	-67^{+10}_{-1}
2	15	$+77^{+18}_{-9}$
3	30	$+185^{+6}_{-0}$
4	15	$+77^{+18}_{-9}$

Geometries with two or more bonding areas to increase the strength of such joints are also possible. Finally, the use of heat or even solvents could make the joints semi-permanent so that they could be reassembled after cleaning. An illustration of the typical bonding geometry is shown in Figure 42.

It is true that it may not be practical to use adhesive joints on liquid oxygen systems because of its incompatibility, and in any event development would be needed to assure that a system is liquid oxygen compatible. However, the lack of liquid oxygen compatibility should not prevent use of this method for fuel and inert gas systems.

A problem which arises in the use of adhesives is that of the difference in the coefficients of expansion for the adhesive and the structural materials. Typical coefficients are approximately:

- 40×10^{-6} in/in/^{o}F - for epoxy, value given is approximate for formulation used in tests; may vary appreciably for other formulations.
- 13×10^{-6} in/in/^{o}F - for aluminum
- 9.5×10^{-6} in/in/^{o}F - for stainless steel

There is, however, a possibility of lowering the thermal coefficient of the adhesive by adding filler material.

Liquid oxygen compatible resins do exist. However, such resins do not necessarily have the best mechanical strength. High strength adhesives at ambient temperatures may become brittle on being exposed to cryogenic conditions while others with good properties at very low temperatures show poor results at ambient temperatures. However, there is the possibility of having the adhesives tailor-made for any application.

TESTING PROCEDURE AND RESULTS

In the tests made an epoxy formulation was chosen to avoid brittleness at low temperatures. This, of course, resulted in a lower strength of the adhesive. For the first two series "T" and "J," unfilled resin has been used. The formulation was:

- 100 pts/w - Epon 828
- 100 pts/w - Veramid 125

The third, or "R" series, was bonded with a filled resin of the formulation:

- 70 pts/w - Epon 820
- 70 pts/w - Veramid 125
- 50 pts/w - Talc

The results of the tensile test of three samples after thermocycling is indicated in Table 4. There seems to be a slight increase of strength compared with the figures in Table 2. This could be due to the fact that the samples were cured further by the thermocycling procedure. To prove this, however, more pull tests would have to be run.

Table 4

TENSILE TEST RESULTS AFTER THERMOCYCLING

No.	Load (lbs.)	Area (in^2)	Tensile Strength (psi)
1	3,900	0.775	5,030
2	3,700	0.710	5,200
3	3,150	0.790	4,000

After the first thermocycling test at dry ice temperature, which did not appear to influence the bond, the same procedure was repeated at liquid nitrogen temperature. The cycles were as shown in Table 3 except for a temperature change in Step 1 from -67° F. to -295° F. All five samples subjected to this test showed no leakage in a vacuum test.

The tensile tests of the samples which were thermocycled between -295° and +185° F. were run at two different temperatures. The results of these tests are given in Table 5. Two of the samples were pulled at room temperature for comparison with previous tensile tests (Tables 2 and 4). Three other samples were tested at liquid nitrogen temperature. This was done in a fixture as shown in Figure 43 and liquid nitrogen was poured into the styrofoam mold to cool the joint. At the end of the test the mold was still about 1/2 filled with liquid nitrogen. Therefore, it can be assumed that the joint was kept at this temperature during the test.

Table 5

TENSILE TEST RESULTS AT TWO DIFFERENT TEMPERATURES

No.	Temperature	Load (lbs.)	Area (in^2)	Strength (psi)
1	Room Temperature	3,610	0.775	4,650
2	Room Temperature	3,750	0.871	4,300
3	Liquid Nitrogen	5,750	0.871	6,600
4	Liquid Nitrogen	5,050	0.711	7,100
5	Liquid Nitrogen	5,850	0.871	6,720

There is an increase in strength at lower temperatures of about 50 percent, although the method of cooling the samples means another temperature shock prior ro loading.

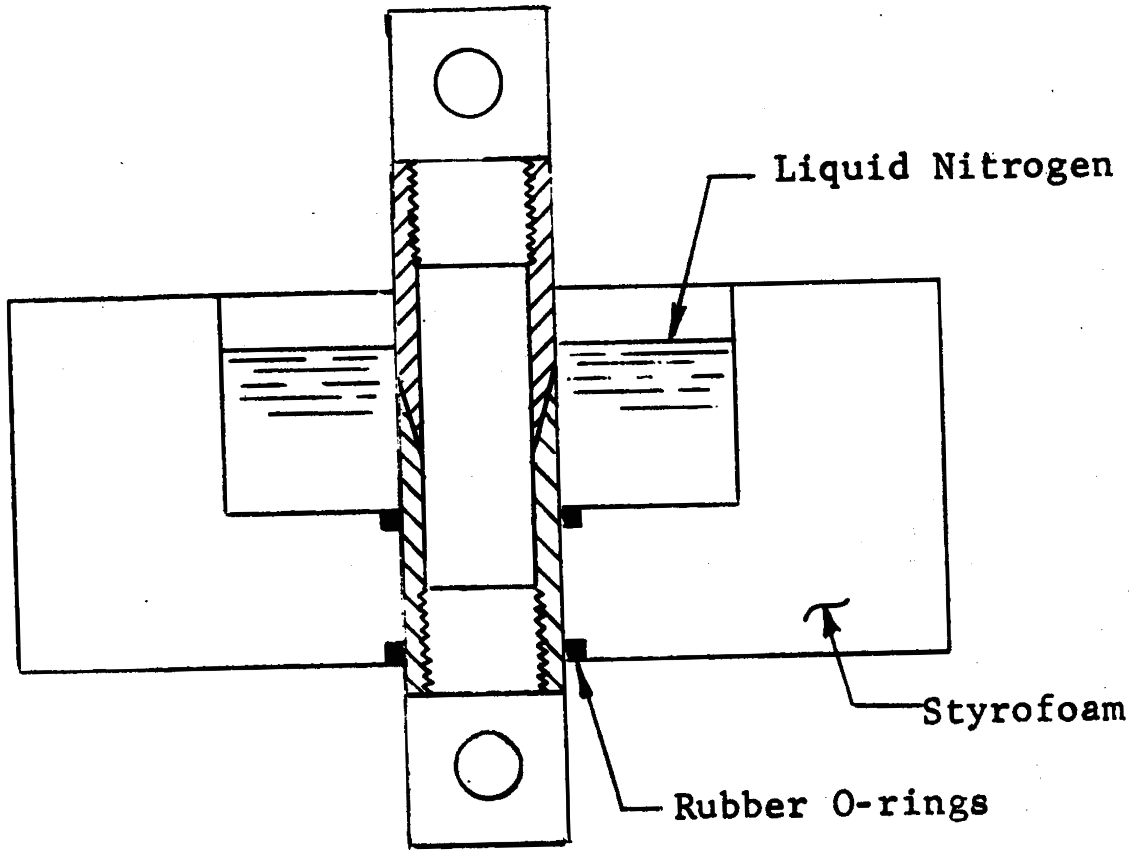


Figure 43. Cryogenic Tensile Testing Fixture

The vibration tests were first performed in a rotating beam machine. Because of the eccentricity of the samples, the results were not useful. After new fixtures had been made for vibration on a shaker, Table 6 samples were vibrated at 200 g's with a momentum load of 150 in-lb for 10^6 cycles with no failure. The load represented a fiber stress of 5320 psi while the shear stress in the adhesive joint was calculated at 1225 psi because of the extended area of the taper. Three of these samples were pulled in tension and no decrease in strength could be observed, as seen in Table 6.

Table 6

RESULTS OF TENSILE TESTS FOLLOWING VIBRATION

Sample	Load (lbs.)	Area (in^2)	Strength (psi)
1	3,340	.743	4,630
2	3,700	.775	4,780
3	3,420	.934	3,660

The remaining five samples were vibrated further while the load was increased. Having a fixed length of test equipment, the g-level was raised. The samples withstood 4×10^6 cycles at 150, 200, 250, and 300 in-lbs moment load and g-levels of 200, 300, and 485 g's. The stresses of the tube and the adhesive are indicated in Table 7.

Table 7

VIBRATIONAL TEST RESULTS

Moment Load (in-lb)	g-level	Cycles	Tube Stress (psi)	Shear Stress Of the Adhesive (psi)
150	200	10^6	5,300	1,125
200	300	10^6	7,090	1,640
250	380	10^6	8,860	2,020
300	485	10^6	10,630	2,450

All samples were leak checked in a vacuum test after each step and were still leak-tight. One of these five samples could not be vibrated at 300 in-lbs and 485 g's since the driving force needed was more than 10 times higher than for the other four and exceeded the maximum driving force of the machine. The vibration tests indicate that for the formulation of adhesive used, the fatigue strength is at least half the normal strength, while calculations are usually made with 1/3 of the normal strength.

Section 8

FUSION WELDING STUDIES

INTRODUCTION

The best possible tube or duct permanent connector is one which adds no weight to the system and thus weighs the same as an equal length of the original pipe or tube. Fusion welding represents a techniques for making such a joint but has several inherent disadvantages. The major problem is that of insuring a high level of cleanliness of the system; that is, of assuring that the welding process will not generate dirt. Therefore, welding studies have been made with respect to cleanliness attainable. Specifications MSFC-SPEC-164 and 10419906B were taken as a guide for these tests.

DESCRIPTION OF TESTS

Two approaches were used to detect dirt generated by the welding process. The approaches were:

1. To clean the samples to be welded and check the cleanliness of these samples after the welding.
2. To investigate the generation of particles by the welding process.

Samples suitable for butt welding were made from 2 inch outer diameter aluminum and stainless steel tubes. Prior to welding, the pieces were pickled and cleaned in the following way:

- Cleaned in alkaline cleanser at 180°F. (OAKITE No. 23, 8 ounces per gallon)
- Rinsed
- Pickled in a 130°F solution consisting of one gallon of nitric acid, forty ounces of No. 90 actane (Fluoride salt) and two and one half gallons of water.
- Rinsed in cold water
- Rinsed in deionized water
- Dried in oven at 190°F

Tubes were joined using a tungsten arc inert gas welding system mounted on a special set up which insured an argon atmosphere inside and outside the tube. To provide an oxygen free atmosphere the tube pieces (in place) were flushed with argon for five minutes. No special seam preparation was given to the samples welded. A butt joint with no filler material added was made so that undercutting of the weld was inevitable. All samples tested were found leak-tight in a mass spectrometer leak test.

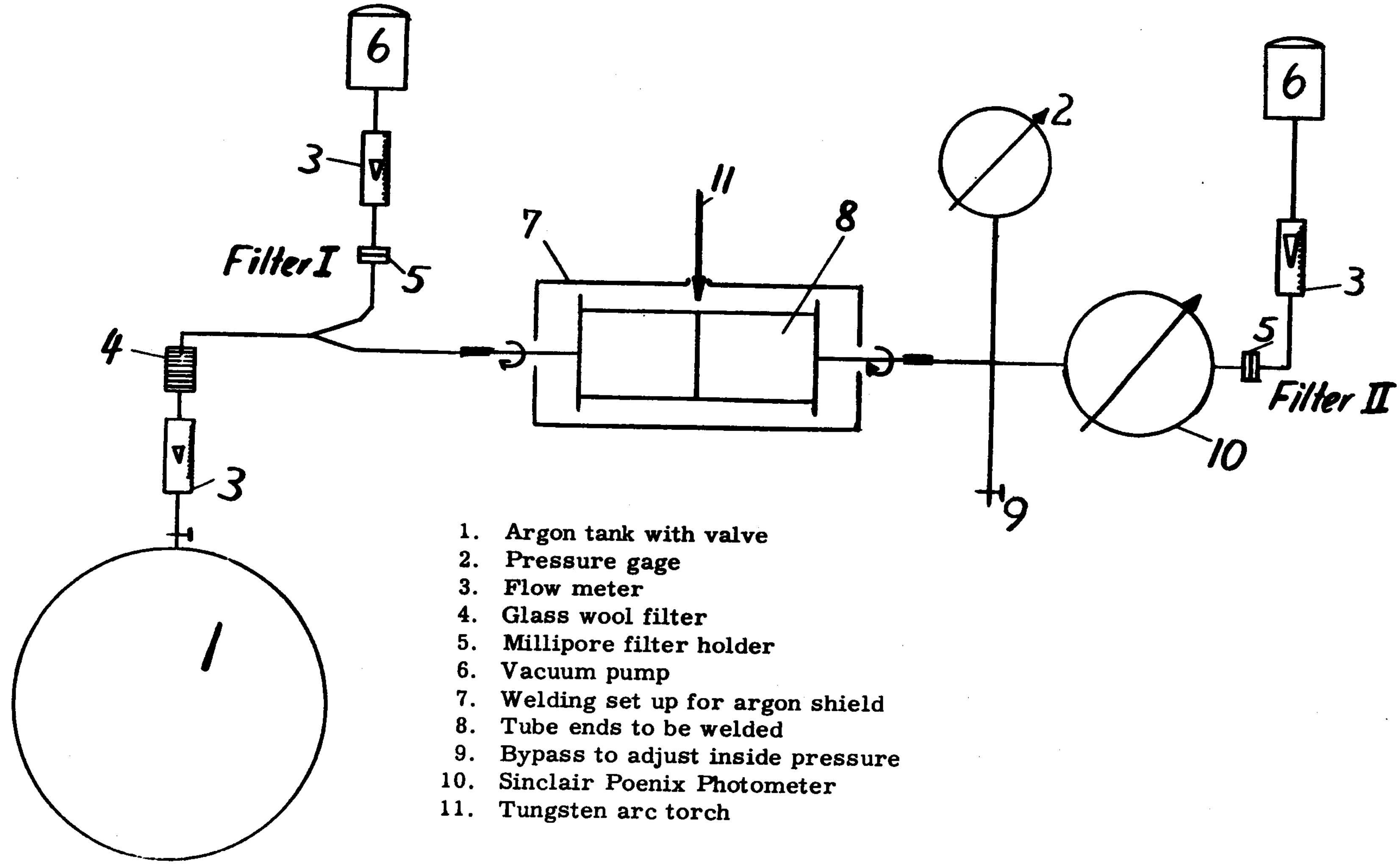
A commercial grade aluminum tube and a conventional grade of argon were used for these tests. No special welding equipment was employed, no splatter due to impurities of the material occurred during welding and the results can very easily be repeated and have been repeated as reported.

As mentioned earlier, it is of major interest to learn about the generation of particles from the welding process itself, since this knowledge is important in determining the suitability of fusion welding for permanent connectors. An attempt was made to determine and compare the number of particles on a tube greater than 20 microns before and after the welding, but this was inconclusive because of contamination from sources not related to the welding process, such as from the air.

A second technique for determining whether the welding process generated dirt was devised and is pictured in Figures 45, 46, and 47, and is shown schematically in Figure 44. Referring to Figure 44 one finds that argon is taken from the bottle (1) and run through a glass wool filter (4). By using Filter I (5) the argon can be checked for particles before it is utilized to flush the inside of the tube samples to be welded (8). The outside of the tube is shielded by the argon supply of the torch (11). After passing the welding zone the argon stream, at the inside of the tube, is sucked through a "Sinclair Phoenix" photometer (10) and a "Millipore" filter (5) in order to check for generated particles. The "Sinclair Phoenix" photometer (10) gives an instant reading and once taken the size and number of particles generated can be determined by examining the "Millipore" filter under a microscope.

For the welding process, it is necessary to prevent any inside pressure. Therefore, again referring to Figure 44, a monometer (2) is kept at a constant setting of one half inches of water. The flow rates are dictated by the measured particle size rather than the capacity of the photometer. Therefore, it is necessary to have a bypass (9) in order to use a variable flow rate, while the instruments work at a constant one. Flow meters (3) located at each side measure the actual flow through Filters I and II and the photometer. As the tubes to be welded have the biggest cross-section in the whole system, the geometry of the tube samples (2 inches outer diameter, 0.049 inch wall and 2 inches long) demands that the flow velocity of the argon gas at least equal the falling velocity of the particles. Falling velocity of particles is a function of particle size. Thus, by choosing a flow rate of 50 ft^3/hr all particles smaller than 60 microns in diameter are transported. This size particle is visible to the naked eye.

The finding of particles on the filter does not give the exact number, as the portion of the filter on which particles were counted has to be related to the whole filter area, and the flow rate through the filter has to be further related to the overall flow rate through the welded tube. Therefore, to get a correct count of how many particles in the critical size range have been generated, both the total gas flow through the tube and the flow through



1. Argon tank with valve
2. Pressure gage
3. Flow meter
4. Glass wool filter
5. Millipore filter holder
6. Vacuum pump
7. Welding set up for argon shield
8. Tube ends to be welded
9. Bypass to adjust inside pressure
10. Sinclair Poenix Photometer
11. Tungsten arc torch

Figure 44. Welding Setup Schematic

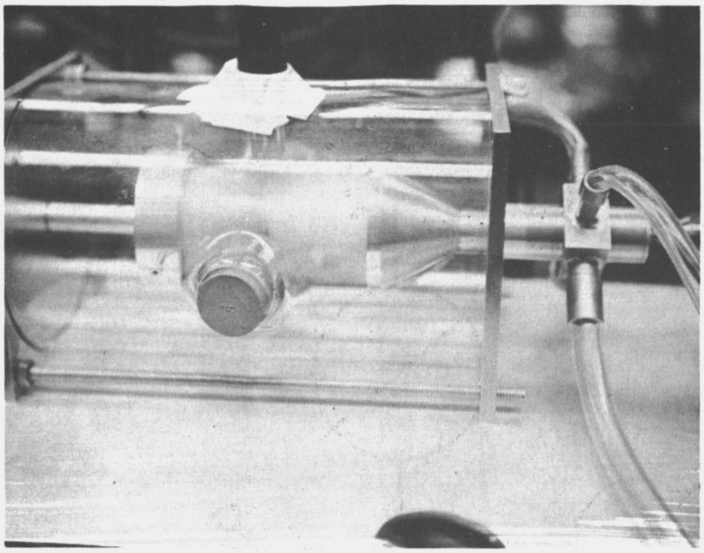


Figure 45. Welding Test Set-up for Purging the Inside and Outside of the Tube with Argon.

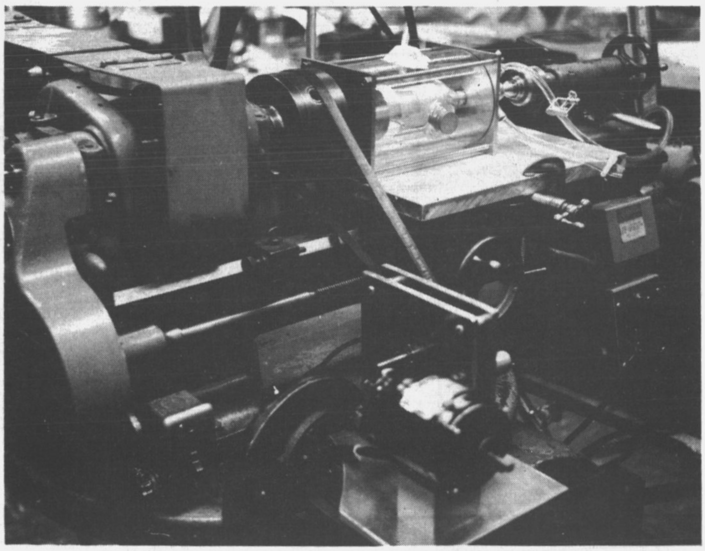


Figure 46. Welding Fixture Mounted on a Lathe for Centering and Driving.

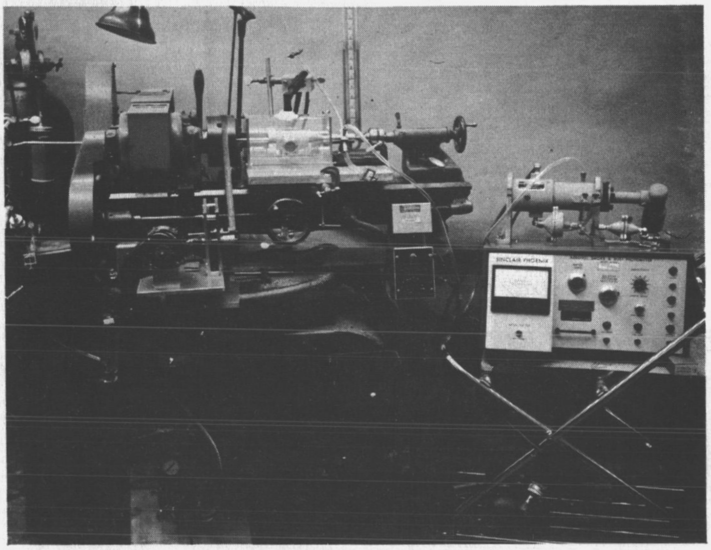


Figure 47. Test Setup as Diagrammatically Illustrated in Figure 44.

Filters I and II were measured. The whole test set-up was cleaned before being assembled. Every piece was finally washed with acetone. Flushing with argon did not show any particles left by the cleaning procedure. Thus, only particles generated during the welding were transported to the instruments and filters.

TEST RESULTS

Preliminary tests were run to check the system and obtain background readings with Millipore filters. Results of these tests are shown in Table 8.

Table 8

PRELIMINARY BACKGROUND TEST RESULTS

Filter No.	Kind of Test Run Argon Stream	Flow Rate (cc/sec)	Time (min)	Total Flow (cc)	Particle Count>20μ On 152 mm Filter Area	Total Count For 3 cm^2 Whole Filter Area	Number of 20μ Particles Per cc
A	Directly off tank through regulator	48	1	2880	14	82.9	0.03
B	Directly off tank through regulator & glass wool filter		1		15	88.8	
C	Through test set up with specially cleaned glass tube	100	1	6000	12	71	0.0118
D	Through aluminum tube (air leak) no heat	100	1	6000	17	100.08	0.0168
E	Through aluminum tube (no heat)	100	2	6000	17	100.08	0.0168
F	Through aluminum tube heated for 2 minutes but not welded	100	2	12000	14	82.9	0.007

The different filters show an almost constant particle reading no matter which parameter was changed. Looking at unused Millipore filters, taken right from the box in which they were shipped, particles of 20μ or larger were found in just the same numbers as in the preliminary tests. Therefore, it is necessary to count the filters before and after each test in order to obtain an accurate evaluation.

The welding tests reported below were run for two and one-half minutes. However, the tubes were flushed with argon for a longer time to make sure that no oxygen was in the system before starting the test and to protect the hot weld from oxidation after welding. At the beginning of the test the argon flush was switched over to the "Sinclair Phoenix" Photometer and the Millipore filter (Filter II). After one-half minute of flushing, welding was started. This took just about one minute, during which time the Millipore filter before the welding fixture (Filter I) was also taking samples. One minute later the argon was shut off from the photometer and the Millipore filters, but not the tube. After cooling was completed the argon was stopped and the parts removed. See Table 9 for results.

Here again test samples were run to give background readings for the designed system. The revolution of the welding fixture did not generate particles. Heating up a straight piece of stainless steel tube without doing any welding did not show any increase in particles, as was found in the preliminary tests in which an aluminum tube was heated. Then five samples of 321 stainless steel weldments which showed good penetration and leak-tightness were made. Although Filter II did not show any increase in particles of the 20μ size range, it showed a coloration, as shown in Figure 48. As this stain could not be resolved under a 400 power microscope and was still a homogeneous coloration, it seemed to be a deposited metal vapor. Thus, the particles generated by the welding process are very small, much smaller than the critical size of 20 microns. The small deviations in the particle count before and after the test can be neglected, as they are due to human error.

The filters of these five samples had been analyzed and all contained manganese. Two of them also contained silver and one of the latter two showed traces of silicon. Manganese was expected as it has the lowest vapor pressure of the elements likely to be present.

These tests were repeated for both 321 stainless steel and 6061-T6 aluminum tubes. The same test set-up was used, but some changes were made. Specifically, rings of filler material cut from the same tubes and pressed flat were added to the joint in order to get a built up weld instead of an undercutting. It worked very well and placed more strength into the welded area. The filters were counted for particles of 5 microns or larger instead of 20 microns, and the results were much the same as before, (See Table 10).

Table 9

WELDING TEST RESULTS

								Filter I							Filter II						
Test No.	Description of the Test	Total Flow Rate		Counting Time	Inside Pressure	Welding Time	Sinclair Phoenix Photometer 0.35 = zero	25 mm D Filter No.	Operation Time	Flow Rate	Total Flow	Particle Count Before	Particle Count After	14-13 Δ	47 mm D Filter No.	Operation Time	Flow Rate	Total Flow	Particle Count Before	Particle Count After	21-20 Δ
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
		ft^3/hr	cc/min	min	in Water	min	Scale		min	cc/sec	cc	20μ and Larger per 152 mm^2				min	cc/min	cc	20μ and Larger per 152 mm^2		
1	Glass tube, nonrevolving	45	21,200	2.5	1.0	--	0.4	13	1	100	6,000	13	15	+2	10	2.5	23,000	57,500	19	19	0
2	Glass tube, revolving	45	21,200	2.5	1.0	--	0.4	14	1	100	6,000	11	8	-3	11	"	23,000	57,500	25	24	-1
3	Stainless steel tube, revolving without heat	62	29,200	2.5	0.5	--	0.4	15	1	100	6,000	25	24	-1	12	"	23,000	57,500	26	28	+2
4	Stainless steel tube, revolving, heated without welding	47	22,200	2.5	0.8	2	0.4	16	1	100	6,000	3	3	0	22	"	23,000	57,500	18	16	-2
5	Welding No. 1	47	22,200	2.5	0.3	1	0.8	17	1	100	6,000	5	5	0	23	"	23,000	57,500	7	9	+2
6	Welding No. 2	51	24,050	2.5	0.3	1	0.8	18	1	100	6,000	6	7	+1	24	"	23,000	57,500	17	19	+2
7	Welding No. 3	50	23,600	2.5	0.4	1.3	1.0	19	1	100	6,000	10	10	0	25	"	23,000	57,500	13	12	-1
8	Welding No. 4	52	24,500	2.5	0.3	1	0.8	20	1	100	6,000	17	16	-1	26	"	23,000	57,500	20	20	0
9	Welding No. 5	50	23,600	2.5	0.3	1	1.0	21	1	100	6,000	15	15	0	27	"	23,000	57,500	20	20	+1

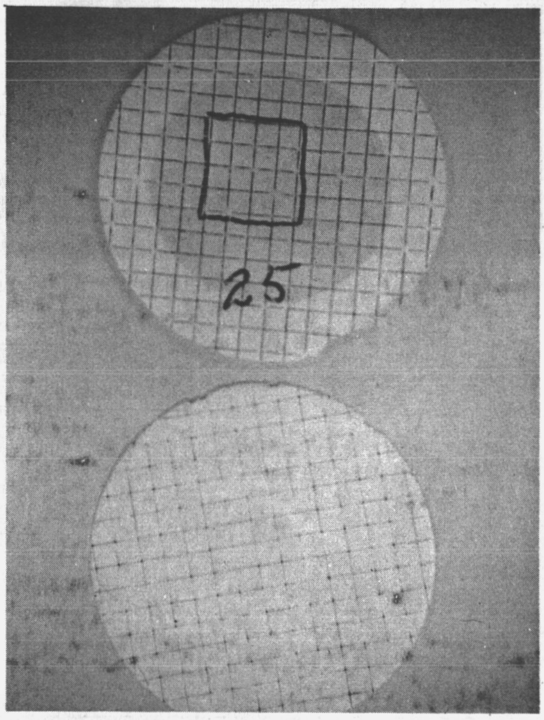


Figure 48. Filter Used in the Preliminary Test (Bottom) and Weldment Test (Top).

Table 10

STAINLESS STEEL AND ALUMINUM TUBE WELDING TEST RESULTS

Test No.	Description of the Test	Total Flow Rate		Counting Time	Overall Flow	Inside Pressure	Welding Time	Rotating Speed	Sinclair Phoenix Photometer Average	Sinclair Phoenix Photometer Peak	Filter I: 25 mm D Filter No.	Filter I: Operation Time	Filter I: Flow Rate	Filter I: Total Flow	Filter I: Particle Count Before	Filter I: Particle Count After	Filter I: Difference Δ 17-16	Filter II: 3 mm D Filter No.	Filter II: Operation Time	Filter II: Flow Rate	Filter II: Total Flow	Filter II: Particle Count Before	Filter II: Particle Count	Filter II: Difference Δ 24-23
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
		ft^3/hr	cc/min	min.	liter	in. Water	min.	rpm	scale	scale		min.	cc/sec	cc.	5μ & larger				min.	cc/min	cc.	5μ & larger per 88.93 mm^2		
1	Glass tube revolving } Preliminary Tests to Check the System	50	23,600	3.0	70.70	0.5	-	3-4	.36	-	A20	1	100	6,000	13	13	0	B20	3.0	16,400	49,200	50	57	+ 7
2	Stainless steel tubes revolving without welding	50	"	3.0	70.70	" .5	-	3-4	.36	-	A19	1	100	6,000	16	15	-1	B19	3.0	16,400	49,200	85	80	- 5
3	Stainless steel tube of Test No. 2 Welded	50	"	2.5	58.65	" .5	60	1.5	2.0	-	A18	1	100	6,000	14	286	+272	BB18	2.5	16,400	41,000	38	142	+104
4	Stainless steel tube welded a small lack in penetration	50	"	2.5	58.65	" .5	40	2	2.0	-	A17	0.5	100	3,000	14	21	+ 7	BB17	2.5	16,400	41,000	27	62	+ 35
5	Stainless steel tube welded; high amperage, good penetration coloration outside	50	"	2.5	58.65	" .5	20	4	3.0	-	A16	0.5	100	3,000	10	12	+ 2	BB16	2.5	16,400	41,000	20	22	+ 2
6	Stainless steel tube welded; 50-60 Amps DC welding current	50	"	2.5	58.65	" .5	60	1.2	1.5	2.0	A15	1	100	6,000	12	10	- 2	B15	2.5	16,400	41,000	71	68	- 3
7	Stainless steel tube welded without ring of filler material	50	"	2.5	58.65	" .5	52	1.5	1.5	2.0	A14	1	100	6,000	10	11	+ 1	B14	2.5	16,400	41,000	87	90	+ 3
8	Aluminum tubes (6061 T6) welded with DC current and Argon/Helium mixture outside the tube; Argon inside	50	"	2.5	58.65	" .5	40	1.8	3.0	3.5	A13	1	100	6,000	14	12	- 2	B13	2.5	16,400	41,000	67	59	- 8
9	Aluminum tubes welded with 30 Amps DC-current no penetration	50	"	2.5	58.65	" .5	50	1.3	2.0	-	A12	1	100	6,000	10	25	+ 15	B12	2.5	16,400	41,000	108	113	+ 5
10	Aluminum tubes welded with 35 Amps DC-current good penetration of the weld	50	"	2.5	58.65	" .5	60	1.3	2-3	4.0	A11	1	100	6,000	8	8	0	B11	2.5	16,400	41,000	79	80	+ 1
11	Aluminum tubes welded with AC-current; motor speeded up when starting welding. No penetration.	50	"	2.5	58.65	" .5	23	1.5	-	1.5	A10	1	100	6,000	7	7	0	B10	2.5	16,400	41,000	71	75	+ 4
12	Test No. II redone after grounding and shielding. Motor speeds again and slows down after awhile, a hole was burnt through	50	"	2.5	58.65	" .5	-	1.5	.36	.36	A10	1	100	6,000	8	26	+ 18	B9	2.5	16,400	41,000	96	90	- 6
13	Lycopodium spores 30μ injected into system smash the filer, no reading possible. Particles are transported in the system.	50	"	2.5	58.65	" .5	-	-	-	4.5	-	-	-	-	-	-	-	B8	2.5	16,400	41,000	-	-	-

Another slight change was made in that the glass wool filter trap was left out of the system, since previously it had no influence on the particle count when argon was taken right from the tank. There was now an increase in the number of particles in a few tests on Filter I prior to welding. These particles only can come from the tank or the regulator. As just the regular equipment of the welding shop was used, the glass wool filter would have trapped these particles. The highest increase occurred in test 3 when the whole system was left for several hours due to a short circuit in the laboratory. However, increase in count on Filter I, column 14, clearly indicates that the increase in count on Filter II, column 22, is due to particles in the argon, and is not generated by the welding.

Looking at the results, there is no increase in particles (five microns or larger) due to welding. The stain on the filter showed a somewhat higher intensity and more coloration but there was no difference in the appearance of the stain generated by the two different materials - stainless steel and aluminum (Figure 49). The higher intensity of the stain could not be eliminated although welding time and alternation of the welding current seemed to have some effect. Welding without filter material also made no difference (Test No. 7, Filter No. B14). The amount of heat generated, or the size of the welding zone at the inside could have an effect on the stain but with the two samples made it is not proven (Filters 18, 17, 16 show little increase in darkness - welding time 60, 40, 20 seconds). If full penetration of the weld is not achieved there is no stain on the filter at all.

The welding of the aluminum was done with direct current instead of alternating current (which is common). The difference between alternating current and direct current welding could not be shown since the alternating current welds were not satisfactory due to interaction with the driving system. Compared with aluminum welds, previously done in the same welding fixture, the heat affected zone seemed to be smaller with alternating current.

Filter B13 showed a normal coloration with no difference from those used during stainless steel weldings. Almost no stain on filter B12 indicated that there was not full penetration of the weld. For the next sample, therefore, the current was raised and the stain on Filter B11 looked very dark.

Welding with alternating current produced poor results in test No. 11. The speed up of the driving motor was compensated during welding by higher current but penetration was not achieved. After a better insulation of the driving system, and careful grounding and shielding, this sample was redone. But as soon as the arc was made, the motor speeded up again and slowed down afterwards. As a result a hole was burned through the wall. Filter No. B10 shows no stain although there was penetration prior to burning. Also surprising was that there were no particles found on the filter. Even the time delay or a little blow-by cannot have affected the reading, since the gas is sucked through the filter by a vacuum pump. Particles if generated, should have been transported.

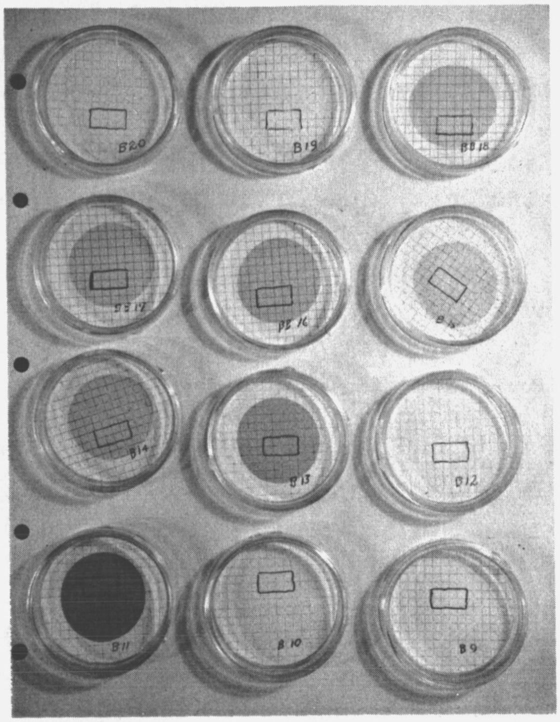


Figure 49. Filters Used in Fusion Welding Particle Counts.

To make sure that particles were transported within the system, a hole was drilled into the weld region of one sample and 30 microns Lycopodium spores were injected. The same flow rate and pressure were applied and the particles were transported through all lines of the photometer to the filter. The filter itself was ruptured because of the amount of particles and no actual count could be made. But the coloration of the pieces and an examination of small sections showed that they were transported through the system.

Spectrographic analysis of the filter, Table 11, showed just about the same results as before. The stains on the filter used for stainless steel welds consisted of Si, Fe, Mg, Cu, Ag, and Mn, all of the same intensity. Other elements with lower intensities were Pb, Cr, Zn. The filters used for aluminum welds showed Si, Fe (out of 5), Mg and Al. Other elements such as Cu, Ag, and Zn were only found in single samples.

Table 11

RESULTS OF THE ANALYSIS OF THE FILTERS SHOWN IN FIGURE 49.

Filter	Si	Fe	Mg	Cu	Al	Ag	Mn	Pb	Cr	Zn	
B20	1	1	1	1		1					Filter blanks
B19	1	1	1	1							without stain
B18	2	2	2	2		2	2	1	1	1	
B17	2	2	2	2		2	2	1	1	1	Filters used
B16	2	2	2	2		2	2	1	1	1	for stainless
B15	1	2	1	2	1	2	2	1	1	1	steel weldings
B14	1	2	1	2	1	2	2	1	1	1	
B13	1	2	3	1	1					1	
B12	2	1	2	1	1						Filters used
B11	2	2	3	1	1						for aluminum
B10	1		1	1	1						weldings
B9	2	2	2	2	1	1					

These tests have been made with ordinary purchased materials and conventional welding equipment. Gas shields, which are also possible in field applications, were used to prevent oxidation. These tests prove that, starting with clean parts and an inside and outside gas shield, good welds can be made without any evidence of contamination by particles five microns or larger. The welding process does generate metal vapors which deposit as particles so fine in texture that they are not resolvable under a 400 power microscope.

Section 9

LINED TUBING AND DUCTS

INTRODUCTION

An ideal tube material is one having high ultimate strength, corrosion resistance to all fluids, and the capability of forming structurally sound and leak-proof connections. A logical approach is the use of a composite material consisting of a liner for optimum corrosion resistance, a casing for strength, and a connector fastened to the tube designed to give a leak-tight joint. It would be desirable if the corrosion resisting material could also be easily sealed, forming a permanent or semi-permanent leak-tight connection.

Metals which fulfill the structural requirements for a tube may react with the fluid contained. In some cases the oxide, fluoride, or other compound generated has physical properties which cause it to become a "protective layer". Thus, upon exposure to ordinary atmosphere, a thin aluminum oxide film forms on aluminum very rapidly and protects the aluminum under it from oxidation. Similarly, chromium oxide protects stainless steel from oxidation or "rusting", and other compounds protect other metals in other environments. Such a protective film, however, may not form, or may be susceptible to cracking and flaking under shock, vibration, or thermal cycling. A liner of suitable material could serve as the protective film for material combinations which are reactive and do not form a suitable self-protective film. Plastics, rubber, ceramics, and unalloyed metals are possible liner materials.

The most promising non-metallic duct materials are plastics. Thermoplastic materials are more compatible with oxidizing agents and hydrocarbon fuels than thermosetting plastics and can also easily produce a leak-tight connection. Connections can be made by heat sealing or the use of a solvent or adhesive. Thermoplastic materials may be used as a duct material where the strength requirements are low or as liners of ducts where their good compatibility and sealing capabilities will be utilized. The most promising thermoplastic is Teflon since it is resistant to all fuels, oxidizers, and monopropellants, except fluorides.

DESCRIPTION AND DISCUSSION OF TEFLON LINED PIPE

A sketch of a Teflon lined pipe is shown in Figure 50. It consists of a Teflon liner inside a metallic pipe having a right angle flare at the ends of each section. Behind the line at each 90 degree flared end is a resilient backing cushion designed to keep the Teflon liner away from the pipe flange and to provide a cushion for the Teflon to Teflon seal between two joined pipes. The Resistoflex Corporation, the manufacturer of this material, has found it necessary to include the resilient backing and a generous radius

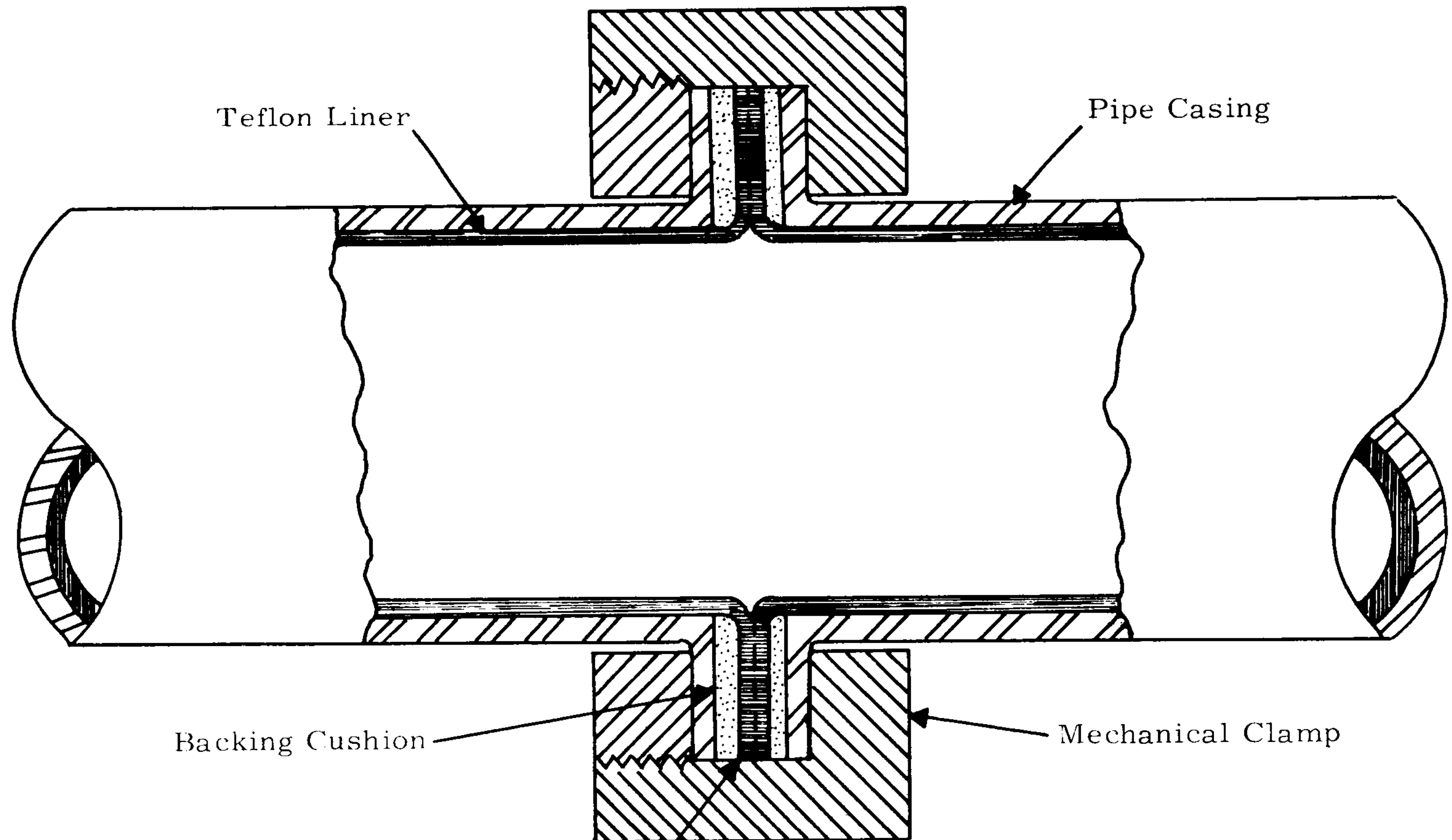


Figure 50. Teflon Lined Pipe.

of curvature of the liner around the 90 degree bend to eliminate problems associated with cold flow of Teflon and differences in thermal expansion between Teflon and the casing metal. A fusion weld is made with the Teflon to form the leak-tight joint and a clamp is drawn over the weld to pull the two pipe sections together forming a Teflon to Teflon seal in addition to the Teflon weld. The clamp also prevents the Teflon liner from extruding when under pressure. The fusion weld and clamp arrangement shown in Figure 50 is a concept of a connector that is not presently available.

The Resistoflex Corporation presently manufactures a TFE Teflon lined pipe with bolted flanges having either schedule 40 ductile or stainless steel pipe as a case. FEP Teflon, which is easier to join by fusion welding than TFE Teflon, is presently being introduced. The TFE lined pipe, designed for the chemical industry, is limited to a temperature range from -100° F to $+500^\circ$ F and pressures below 300 psi. Both limitations are due to the behavior of the TFE Teflon liner. Teflon has an upper service temperature of 500° F and may be used at cryogenic temperatures although it has reduced ductility at these temperatures. Because of Resistoflex's manufacturing process and the limited demand for Teflon lined pipe for cryogenic service, the lower limit has been set at -100° F. The Teflon lined flexible hose used in aircraft has been successfully used to transfer liquid oxygen. No major problem areas are foreseen by Resistoflex in designing a pipe to operate at -420° F. The recommended pressure of 300 psi is based on the manufacturing test currently given to the liner (and limited by the flange connection between sections). Liners are first tested under hydrostatic pressure of 225 psi using dyed water. The liner is then assembled into the pipe casing and given a spark test to uncover any flaws in the liner. Pressures as high as 900 psi have been contained for short time periods. The biggest problem associated with high pressures is the extrusion of the Teflon out of the gap between the two flanges. Proper flange design could eliminate this problem. Leakage by permeation also becomes a major problem at high pressures.

The following problem areas are associated with the use of Teflon lined pipe:

1. Differential in expansion of the liner and casing due to temperature change.
2. Cold flow of the Teflon liner.
3. Heat sealing of the liner of two pipe sections to form a tight joint.
4. Leakage of a fluid by permeation through the liner.

The hoop stresses developed in the liner and casing due to the differentials in radial displacements from temperature changes are not considered a serious problem because of the Teflon's ductility. In the axial direction, however, the liner has a tendency to move relative to the case if not constrained at the ends of the pipe. By proper design of the joint between two sections, any differential changes in axial length of the liner relative to the case can be accommodated. The small radius at the 90 degree bend and the backing cushion are required to accommodate the change in relative displacements. Resistoflex claims to have eliminated problems associated with cold flow by incorporating a radius at the 90 degree flare and using a backing cushion, and a sizeable flare at the joint.

SEALING THE LINER

Teflon lined pipe sections can be joined and bonded by:

- Adhesives or solvents
- Hot gas welding
- High frequency welding
- Heated tool welding
- Friction welding
- Ultrasonic welding

Various procedures have been developed for preparing special surfaces on TFE and FEP Teflon parts to which conventional adhesives will bond. As a result, a good bonding strength is achieved with adhesives in bonding Teflon to steel, aluminum, copper, and plastics.

Hot gas welding is similar to gas welding of metals except hot gas is used instead of an open flame. An open flame cannot be used with thermoplastics because of the intense heat and oxidization.

High frequency welding is based on the creation of local heat. If a plastic with a high power factor is held between two electrodes of a high frequency generator, local heating between the two plastic sheets will occur. TFE is difficult to weld by high frequency welding, but FEP Teflon may be welded by this procedure.

Heated tool welding uses a hot plate or knife which is placed between the two sheets to be welded. When the surfaces of the two sheets have melted, the tool is removed, the two sheets pressed together and bonded. Fluorocarbons are very difficult if not impossible to weld by this method.

In friction welding, heat generated by friction in the interface parts to be welded is used to make the weld. Spin welding employs the frictional heat that is generated by the rotational rubbing of two contacting surfaces. FEP Teflon has been spin welded, but it is a difficult procedure. It may be possible to spin weld a FEP ring because the flanges themselves apply a squeezing force. When the face of the ring melts or softens, the spinning is stopped and welding to the flanges may result.

Ultrasonic welding is a new process requiring further developments. The principle of operation is that ultrasonic pulsations, created by an ultrasonic generator and transmitted to the material to be welded by way of a transducer, cause controllable local melting and welding of the material.

The recommended method of welding FEP Teflon is by a heated tool, hot gas, or solvent. TFE is difficult to heat seal by any of the welding methods.

Teflon like other organic materials is porous resulting in the leakage of gases at a permeation rate of approximately 10^{15} times greater than through metals. The permeation rate of oxygen through Teflon with a one atmospheric pressure differential has been reported to be between 0.39 and 1.2 grams/100 in^2/day/mil. A permeation rate of 1 gram/100 in^2/day/mil is equal to 1.8×10^{-6} cm^3-mm/cm^2-sec-atm. As a comparison, hydrogen has a permeation rate through aluminum of 3×10^{-22} cm^3-mm/cm^2-sec-atm.

The expression for flow rate through a solid is given by

$$Q = DA \frac{\Delta P}{L}$$

where D is the permeation rate, A the surface area normal to flow, L the length of leakage path, and ΔP the pressure differential.

Using this expression, a flow rate of 28×10^{-6} pounds of gaseous oxygen per day will be lost through a one foot section of two inch diameter 62 mil wall Teflon liner, where the pressure differential is one atmosphere. However, the permeation rate may be decreased by treating the surfaces or adding fillers to the Telfon. Obviously, the surface treatment or filler must be compatible with the fluid to be used.

Section 10

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